ASTROBIOLOGY
Volume 15, Number 1, 2015

DOI: 10.1089/ast.2014.1219

Education Article

Developing the Critical Thinking Skills of Astrobiology Students through Creative and Scientific Inquiry

Jamie S. Foster[1] and Judith D. Lemus[2]

Abstract

Scientific inquiry represents a multifaceted approach to explore and understand the natural world. Training students in the principles of scientific inquiry can help promote the scientific learning process as well as help students enhance their understanding of scientific research. Here, we report on the development and implementation of a learning module that introduces astrobiology students to the concepts of creative and scientific inquiry, as well as provide practical exercises to build critical thinking skills. The module contained three distinct components: (1) a creative inquiry activity designed to introduce concepts regarding the role of creativity in scientific inquiry; (2) guidelines to help astrobiology students formulate and self-assess questions regarding various scientific content and imagery; and (3) a practical exercise where students were allowed to watch a scientific presentation and practice their analytical skills. Pre- and post-course surveys were used to assess the students' perceptions regarding creative and scientific inquiry and whether this activity impacted their understanding of the scientific process. Survey results indicate that the exercise helped improve students' science skills by promoting awareness regarding the role of creativity in scientific inquiry and building their confidence in formulating and assessing scientific questions. Together, the module and survey results confirm the need to include such inquiry-based activities into the higher education classroom, thereby helping students hone their critical thinking and question asking skill set and facilitating their professional development in astrobiology. Key Words: Scientific inquiry—Critical thinking—Curriculum development—Astrobiology—Microbialites. Astrobiology 15, 89–99.

1. Introduction

Scientific inquiry is the process by which individuals make observations, formulate questions, and generate data, ultimately improving the state of knowledge of the natural world (National Research Council, 1996, 2000). Training astrobiology students in scientific inquiry is critical, as it not only enables them to acquire a fundamental understanding of current scientifically accepted ideas but also endows the students with the critical thinking skills to improve their scientific learning process in a multidisciplinary field such as astrobiology (Zion and Sadeh, 2007). However, the practice of teaching scientific inquiry can be often overlooked in the higher education classroom, as the emphasis is often placed on the transmission of knowledge rather than facilitating the students' ability to integrate, analyze, and synthesize these facts. In those courses where inquiry-based activities, such as group discussions and open questioning of the material, were included into the curriculum, significant increases in post-course knowledge of the participants were observed (Hake, 1998). Such studies signify the need and importance of incorporating inquiry-based activities into higher education classrooms.

One key facet in promoting scientific inquiry among astrobiology students is the development of critical thinking skills. Critical thinking is an active process that requires students to analyze information through synthesis and integration of otherwise seemingly independent facts (Bailin, 2002). Eventually, students are asked to make inferences on its validity and relevance to the subject matter being discussed. Teaching this important skill set often starts with helping students learn how to ask high-quality, analytical questions of the presented scientific material. Knowing how to ask the ''right'' type of question in science is an important component of an emerging scientist's repertoire and the scientific inquiry process. In addition to helping students'

[1]Department of Microbiology and Cell Science, University of Florida, Space Life Science Lab, Merritt Island, Florida.
[2]Hawai'i Institute of Marine Biology, University of Hawai'i, Kane'ohe, Hawai'i.

build their skill set in formulating scientifically valid questions, it is equally important that students gain experience in asking those questions in both the classroom and professional settings. Asking questions in a public setting can often be intimidating to students, as they can often fear disapproval of their ideas or questions (Vogt, 2008; Hurtado *et al.,* 2009). Activities that enable students to practice asking their questions can help develop student confidence (Foster and Drew, 2009).

An important aspect of helping students gain the ability to ask pertinent questions and build their skill set is providing students the opportunity to explore the fundamental creative processes associated with scientific inquiry. Although science is about systematic observations, experimental evidence, and logical thought, the most innovative ideas and breakthroughs come from creativity. Creativity can lead to the development of novel and valuable products, whether it is a new movement in art, a leap in technology, or important scientific discoveries (Akin and Akin, 1998; Sternberg and Lubart, 1999). Both the artist and the scientist deconstruct the world around them, then through their observations reorganize the imagery, events, or data to help find new relationships or associations not previously detected. Cognitive dissonance is another source for innovation and creativity in science. Cognitive dissonance is a psychological term to describe the feeling of discomfort when one experiences two conflicting ideas (Festinger, 1957). This discourse of conflicting ideas or theories can be a major driver in the scientific process. If new scientific evidence is in conflict with an existing theory, then additional experimentation can either refute those conflicting ideas or lead to new theories about the idea in question.

To expose astrobiology students to the processes of scientific inquiry and build their creative and critical thinking skill sets, we developed a learning module that can be adapted to most STEM (*i.e.,* science, technology, engineering, and mathematics) courses. There were two key objectives with this curriculum activity. The first was to help students understand the basic processes, both creative and scientific, of inquiry-based learning. The second objective was to provide students with a hands-on opportunity to practice and hone their critical thinking skills in a low-pressure setting. We chose art as a representation of an artifact that was creatively produced yet accessible to students, with the goal of allowing students to practice asking critical thought questions with creative objects more familiar than scientific visualizations. Building student capacity in critical analysis of scientific images, including generating questions, was one objective of the exercise; therefore we sought to introduce the concept of critical thinking and analysis through questioning using a famous artistic image. In our view, generating questions (which are essentially ideas without an immediate obvious solution) is a key skill in critical thinking and requires not only prior knowledge and objective analysis but also a fair amount of creativity (Chin and Osborne, 2008). Moreover, the connections and mutual influences between creative expression and thought in science and art have been well documented by historians, philosophers, and practitioners of both disciplines (Root-Bernstein, 2000; Simon, 2001; Mandelbrojt, 2006; Kolijn, 2013; Root-Bernstein and Root-Bernstein, 2013). By presenting scientific visualizations alongside an artistic expression in which critical analysis is embedded (Picasso's *Guernica*), we proposed to students the concept that scientific visualizations can be both analytical and creative. We therefore approached scientifically oriented thought from two separate, but related, expressions of creative critical analysis: visualization of science through imagery, and analytical ideation (generation of ideas through questioning).

The overall learning outcomes of the exercise were to enable students to (1) describe the fundamental principles associated with scientific inquiry, (2) formulate scientific questions that are analytical in nature, and (3) critically evaluate and assess the strengths and weaknesses of scientific research. In this paper, we discuss the architecture of the inquiry exercise, as well as present pre- and post-course surveys that examine students' perceptions of scientific inquiry and the effectiveness of the activity in an astrobiology course over three consecutive years. Through the development and implementation of these inquiry-based activities, students can begin to experience the multilayered processes associated with the scientific method, as well as improve their own professional development and overall understanding of astrobiology research.

2. Methods

2.1. Pre-course student surveys

The participants of this study were undergraduate science majors, primarily juniors and seniors, enrolled in a multidisciplinary Astrobiology (MCB 3703) elective course offered by the Department of Microbiology and Cell Science at the University of Florida from 2010 to 2012 (taught by J.S. Foster). The astrobiology course included topics such as planetary and geological sciences, biogeochemistry, and microbiology. The overall goal of the course was designed to introduce life science students to the geological and biochemical processes that facilitated the origin and evolution of life on Earth. Additionally, several skill-building exercises were included in the course to help students prepare for a professional career in science.

On the first day of class, anonymous surveys were conducted to evaluate the students' perceptions of creative and scientific inquiry, as well as assess their own experiences and abilities in asking questions in a professional setting (*e.g.,* departmental seminar, scientific meeting). The students' perceptions were assessed by using a combination of a Likert scale (Likert, 1932) and a series of multiple-choice questions. For the Likert scale portion of the survey, students were asked the extent to which they agreed or disagreed with a particular statement. Response options ranged from *strongly agree* (5), *somewhat agree* (4), *neither agree nor disagree* (3), *somewhat disagree* (2), and *strongly disagree* (1). The multiple-choice questions assessed the frequency that students were asked to utilize creative thinking skills in their courses, as well as the nature of the scientific questions that often come to mind when they watch a scientific presentation. The surveys were analyzed by examining the frequency distribution of student responses for each year, with the mean and standard deviation for each question reported by year.

2.2. Scientific inquiry exercise structure

The design of our approach comes from the premise that generating and critically analyzing questions are central to scientific inquiry learning. However, undergraduate students can be reluctant to ask questions in the classroom unless a positive learning environment for questioning is created (Pedrosa-de-Jesus *et al.,* 2004, 2012). At the same time, these inquiry skills require creative thought (Root-Bernstein and Root-Bernstein, 2013) and increasingly the interpretation of complex visual images. By combining the need to provide opportunities for students to become confident in questioning with our interest in fostering stronger connections for students between scientific thought, creativity, and critical analysis, our lesson introduced questioning/ideation and critical analysis with, first, a famous visual example of creativity, and then scientific visualizations. These visualizations were the platform for students to practice generating scientifically oriented questions (Chin and Osborne, 2008).

The scientific inquiry exercise was conducted in three consecutive years—2010, 2011, and 2012—with the number of participants ranging between 20 and 25 each year. The scientific inquiry–learning module comprised three distinct components (Table 1) and was conducted during the beginning of the semester (*e.g.,* week three of the course). First, students were introduced to the role that creative processes play in developing scientific ideas and concepts. The students listened to a presentation by the instructor that discussed basic concepts associated with creative and scientific inquiry, such as cognitive dissonance, recognizing cognitive dissonance, and how making observations and posing questions can lead to the development of new insight and scientific knowledge. The lecture used Albert Einstein and Pablo Picasso as models for the inquiry exercise, as both the scientist and artist contemporaneously published several of their major works in the early part of the 20th century. Students were asked to compare and discuss the creative processes associated with developing a novel scientific theory, such as General Relativity (Einstein, 1916), with that of an artistic endeavor, such as Picasso's *Guernica* painting. After the students had been introduced to the basic concepts associated with using creative processes in scientific inquiry, they were asked to observe and deconstruct Picasso's *Guernica* painting and then generate several questions about the work of art. Often in science students are asked to assess and evaluate visual images for pattern-based data (*e.g.,* petrographic thin sections, DNA gel electrophoresis), and this component of the exercise was to provide students with a more familiar, perhaps less intimidating, image for them to begin to practice this skill set. Students were also asked to self-assess the nature of their questions and categorize the questions as being analytical, informational, or emotional in nature.

The second component of the exercise involved transitioning from the creative processes typically associated with artistic endeavors to those of a scientific nature by using scientifically generated images of natural objects. First, students were given a series of guidelines on the general approaches for generating a scientific question that included using observations, logic, and their own curiosity (Supplementary Fig. S1, available online at www.liebertonline.com/ast). In these guidelines, students were told to consider the following when making their observations: (1) all objects

Table 1. Overview of Scientific Inquiry Exercise

Module component	*In-class or at home activity*	*Brief description*	*Estimated duration*[a]	*Materials needed*[b]
Creativity in Science	In-class	Lecture introduction to basic concepts associated with creativity in scientific inquiry; practice exercise where students ask questions about artwork then self-assess their questions	25 min	PowerPoint slides
Scientific Inquiry	In-class	Students observe several scientific images (*e.g.,* thin sections, micrographs, DNA gels) and pose questions regarding their science content.	25 min	Scientific images
Scientific Podcast and Analysis	At home	Students listen to a 10 min podcast on a scientific topic related to the course. Students are asked to evaluate science content, assess whether research results support the presenter's conclusions, and generate scientific questions about the presented research material.	50 min	Podcast of scientific material
Post-Exercise Discussion	In-class	Students discuss the podcast and their assessments and self-evaluate their scientific questions regarding the podcast. Additionally, students complete a post-exercise survey.	50 min	Student assignments and surveys
Learning Outcomes	At the end of this exercise, students will be able to • Describe the processes associated with scientific inquiry • Formulate scientific questions that are analytical in nature • Critically evaluate and assess the strengths and weaknesses of scientific research			

[a]Estimated two 50 min classes dedicated to completing the scientific inquiry exercise.
[b]Examples of all materials are provided at http://jamiefosterscience.com/building-science-skills.html.

(*i.e.,* minerals, molecules, genes) must have arisen somehow, (2) these objects must exhibit certain properties or functions, and (3) these objects must at some point cease to exist. The students were then given some suggested questions to think about (even if they did not have the answers) when they were making observations or listening to a presentation. These suggestions included, but were not limited to, the following:

- ''Is the object changing with time?''
- ''How did it form?''
- ''What is its relationship to other objects?''
- ''How does this object function?''
- ''From what is this object made?''
- ''How does this object degrade?''

The students were then shown two abstract, unlabeled, high-magnification images of a 3-D eukaryotic cell generated with cryo-electron tomography and an artificially colored scanning electron micrograph of fish scales. Students were asked to pose several questions using these guidelines about what they observe and discuss how analysis of these images might improve scientific knowledge about the subject matter. Students were also provided guidelines on how to assess the overall quality of their questions. Students were told that ''good'' scientific questions often lead to an improved understanding and that ''okay'' questions were those that provided some information but no improved understanding of the material. The students were also advised that a ''bad'' scientific question was one that did not provide information or understanding of the material and might in fact lead to misinformation regarding the subject. Students were given a series of example questions and asked to assess the overall quality of the questions and characterize the questions as good, okay, or bad.

Lastly, the students participated in a practical exercise where they listened to a pre-recorded scientific podcast and were asked to think about the processes of cognitive dissonance and develop a series of analytical questions regarding the content. The subject matter of the pre-recorded podcast included a brief (*i.e.,* 8 min) seminar on modern microbialites. Microbialites are carbonate buildups that form as a result of the interactions of microbes with their surrounding environment (Burne and Moore, 1987). Microbialites are ancient ecosystems with fossils that date back over 3.5 Ga and can be characterized by their geological macro- and microstructures (Burne and Moore, 1987). The podcast specifically compared the functional gene diversity of microbes associated with two types of microbialites, laminated stromatolites an unlaminated thrombolites. The research included in the podcast was derived from two recently published studies on the functional gene complexity associated with these lithifying communities (Khodadad and Foster, 2012; Mobberley *et al.,* 2013). The podcast contained various data slides, graphs, and interpretations of the two types of microbialite communities. The students had been previously exposed to the fundamental concepts associated with the geological and microbiological processes of carbonate mineralization in several prior class lectures. During the podcast, the instructor intentionally made overstatements and some omissions regarding the presented research, with the intent to provide the students with the opportunity to recognize the phenomenon of cognitive dissonance and gain critical thinking experience by evaluating and developing questions regarding the science content. The students then articulated their questions in class and as a group discussed the qualitative attributes (*i.e.,* analytical or informational-based questions) as well as the quality (*i.e.,* good, okay, bad) of the various questions.

The complete activity sheet is provided in Supplementary Fig. S2, and the companion lecture slides and pre-recorded podcast are freely available at http://jamiefosterscience.com/building-science-skills.html. In 2010, all three components were completed as in-class activities that spanned two classroom periods. However, based on feedback from the students, in 2011 and 2012 only the first two components were completed in class, and the third section was assigned as homework to provide the students with additional time to work on the activities. A discussion regarding the nature of the students' comments and questions was conducted during the next class.

2.3. Post-exercise student self-assessment surveys

Upon completion of the exercise, students were provided with an anonymous post-exercise survey that assessed the students' perceptions regarding the usefulness of the exercise and whether it helped improve their scientific inquiry skill set. The survey was conducted similarly to the pre-course survey in that students were asked the degree to which they agreed or disagreed with a given statement using a Likert scale. The frequency distribution of student responses are reported, and the surveys were also analyzed by examining shifts in the means of the Likert scale responses between years with the use of a Fisher's exact test with two-sided analysis. Based on the authors' assessment of the 2010 post-activity survey, additional survey questions were added to the 2011 and 2012 post-exercise surveys so that the students' experiences and attitudes about the learning module could be more thoroughly explored.

3. Results

3.1. Students' prior experience with creative and scientific inquiry

Prior to the start of each astrobiology course, students were asked to self-assess their own experiences regarding scientific inquiry in both a classroom and professional setting. Specifically, students were asked the frequency at which they are required to use their creative thinking skills in their science courses (Fig. 1a). Results indicated that in all three years a strong majority of students thought that they used their creative skills either very or somewhat regularly (68–70%) in their course work at the University of Florida. Although the term ''creative thinking skills'' was not predefined prior to the survey, the results were consistent between years ($p \geq 0.100$). In each year, however, between 13% and 15% of the students responded that they never or rarely use their creative thinking skills in their course work, with another 15–20% indicating they use these skills only occasionally.

Despite the majority of students indicating that they use these skills in the classroom, the students' responses suggested they were less comfortable with putting their creative thinking and inquiry skill set into practice in a professional

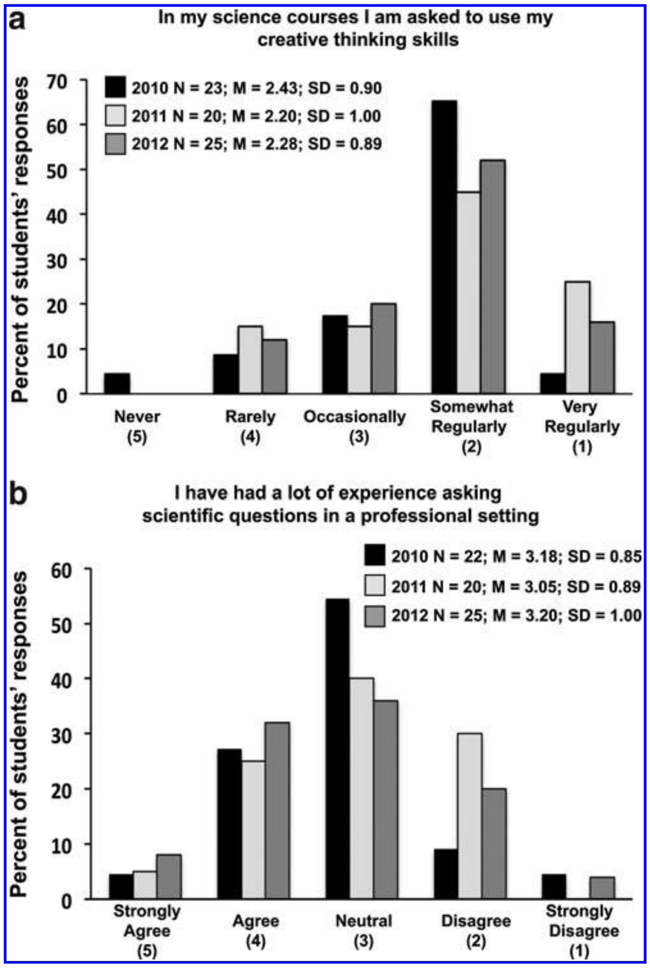

FIG. 1. Pre-course assessment of students' prior experiences with scientific inquiry in both (**a**) classroom and (**b**) professional settings (N, number of students; M, mean response; SD, standard deviation of responses).

setting (Fig. 1b). A professional setting was defined to the students as any nonclassroom experience such as a departmental seminar or scientific conference. Although between 30% and 40% of the students strongly agreed or agreed that they have had experience using their critical thinking skills in a professional setting, a larger subset of the students were neutral on the subject (36–55%), indicating that they neither agreed nor disagreed with this statement. The number of students that disagreed with this statement varied between years. In 2010, only 9% of the students disagreed that they had extensive experiences asking scientific questions outside the classroom, whereas in 2011 and 2012 this response rose to 30% and 20%, respectively.

In addition to being asked about their experience level, students were also asked the nature of the questions they think about during a scientific presentation (Fig. 2). In the survey, the students had the option to select as many categories as they wished. Results suggest that the vast majority of the surveyed students do formulate questions when they watch scientific presentations; however, the type of questions varied. The two major categories of students' questions were ''How might this information be applied to other areas of science?'' and ''What are the missing pieces regarding the presentation?'' with approximately equal representation of the student responses in all three years, 29–40% and 33–42%, respectively. To a lesser extent, some of the students thought about how the research material related to their lives (21–32%), and a few appeared to have had difficulty following the content of presentations (0–7%).

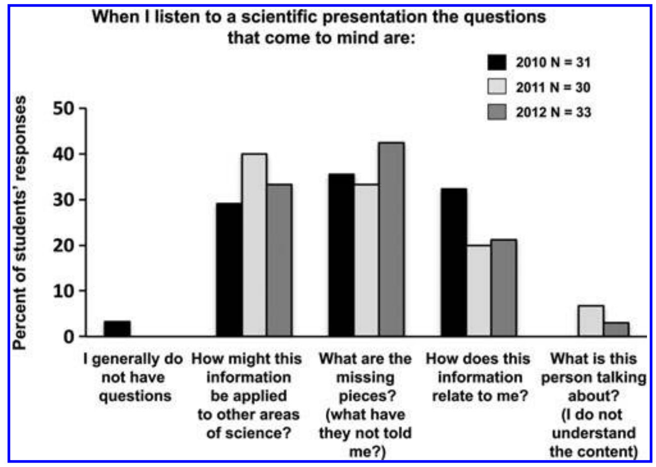

FIG. 2. Pre-course self-characterization of the types of questions that students contemplate during scientific presentations (N, number of students).

3.2. Student responses in scientific inquiry exercise

During the activity, students were asked to formulate questions based on several artistic and scientific images, as described in the methods section. After students were provided some basic introduction into the underlying processes involved in scientific inquiry, they were asked to observe the painting *Guernica* by Pablo Picasso and formulate several questions about this work of art. Representative questions from students are provided for each year the activity was conducted (Table 2). After writing their questions, students were then asked to self-assess their own questions and categorize them as analytical (*i.e.,* those questions that promote understanding of the material or can be tested scientifically); informational (*i.e.,* questions that give background details yet do not necessarily promote understanding of the subject matter); or emotional (*i.e.*, what feelings does this artwork invoke). The vast majority of the students perceived their own questions as analytical; however, upon instructor analysis of the questions, approximately half the questions were deemed informational in nature. For example, a student asked about the tools required to make the painting rather than analyzing the painting itself, yet that student considered the question analytical (Table 2). When examining all questions from 2010 to 2012, trends emerged in the general types of question. Again, many of the questions were informational in nature, as numerous students asked about background information, such as the historical context of the painting or why certain objects were present in the painting rather than assessing their meaning. However, some students did generate analytical questions such as what various symbols or painting techniques, such as the lack of color, represented. Other students wrote more emotional-based questions regarding the inspiration of the painting and

Table 2. Representative Student Questions Posed during Each Section of the Scientific Inquiry Exercise

Exercise component	*Emotional-based*	*Informational-based*	*Analytical*
Art Images	What does the violence in the image represent?	What tools were used to create this painting?	What is Picasso trying to convey with the dismembered people in the painting?
	What was the inspiration for this painting?	Are the people portrayed in the painting trying to escape from somewhere?	Is there significance to where the body parts are placed? For example, which way the characters are facing?
	This painting seems highly emotional. What possible event could have happened to touch Picasso in such a way?	Why is the color scheme in black and white?	What is the significance of the light bulb in the painting?
	Is this painting supposed to be an actual event, or is it just an outward presentation of an inward expression?	During what historical context was the painting created?	What does the incorporation of the animals have to do with the meaning the author wants to convey?
Scientific Images		How were the figures in this image created?	What is the significance of the different colors in the image?
		Was this image taken with a fluorescence microscopy given that the background is black?	Does the repeating pattern infer something about its function?
		What is the purpose of using colors that are so contrasting?	Are there other ways of getting the same image but using a different technique?
		What is the lateral view of the image supposed to reveal as apposed to the view from the top?	How will this help future experiments or identification of organisms?
Microbialite Podcast		How were the carbonate structures determined to be microbial?	Does the internal organization of microbialites infer the type of microbes that contributed to its formation?
		Why do different types of microbialites have differing structures?	How can it be concluded that carbohydrate synthesis is the most important subsystem in stromatolites compared to thrombolites when only 5% of the metagenome was sequenced?
		If microbialites once populated most of Earth's surface, what caused this decline?	Could these modern microbialite analogues to ancient microbial communities be used for understanding the last universal common ancestor?
		What are the advantages and disadvantages of using pyrosequencing? Are there alternative methods to fulfill this research objective?	What is the role the location and environmental conditions play in the microbial composition of microbialites?

Note: questions are representative questions derived from all three years of the exercise (2010–2012). Categories of questions reflect the domains of learning based on Bloom's taxonomy (Bloom, 1956).

wondered about the creative processes the artist must have experienced to paint such graphic imagery.

The second component of the inquiry exercise was designed to help students gain experience with asking questions of a scientific nature. After the artwork exercise, students were provided a series of guidelines for asking scientific questions (as described in the methods section) and then shown two images generated by electron microscopy (*i.e.,* a 3-D image of a eukaryotic cell and an artificially colored image of fish scales). As in the artistic image section, several students still often confused analytical and informational-type questions. Students often questioned how the image was generated rather than assessing the image contents. Despite a slight majority of informational-based questions, students did inquire into the meaning of the images and how the images could be used to improve understanding of the subject matter (Table 2).

In the last segment, students watched a short podcast on modern microbialites and then formulated questions based on the science content. Representative questions are listed in Table 2. Again, students wrote an even mixture of informational-based and analytical questions, which suggests additional training regarding the differences between these categories is necessary. Most of the informational-based questions targeted background information of the microbialites and why certain methodologies were chosen. The analytical-based questions focused more on the data interpretation. For example, several students questioned how certain conclusions could be made when such a small data set was presented in the podcast (Table 2). Such questions indicate the students were willing to question the presented conclusions and form their own opinions regarding the presented material. Other students inquired how the results could then be used to improve understanding of the biological processes associated with carbonate precipitation in the microbialite communities. The results suggest that students were using the provided guidelines to assess the functions and relationships of the different microbes in the microbialite ecosystems; however, the prevalence of informational-based questions suggests that students were not fully integrating their knowledge from prior lectures into the inquiry exercises.

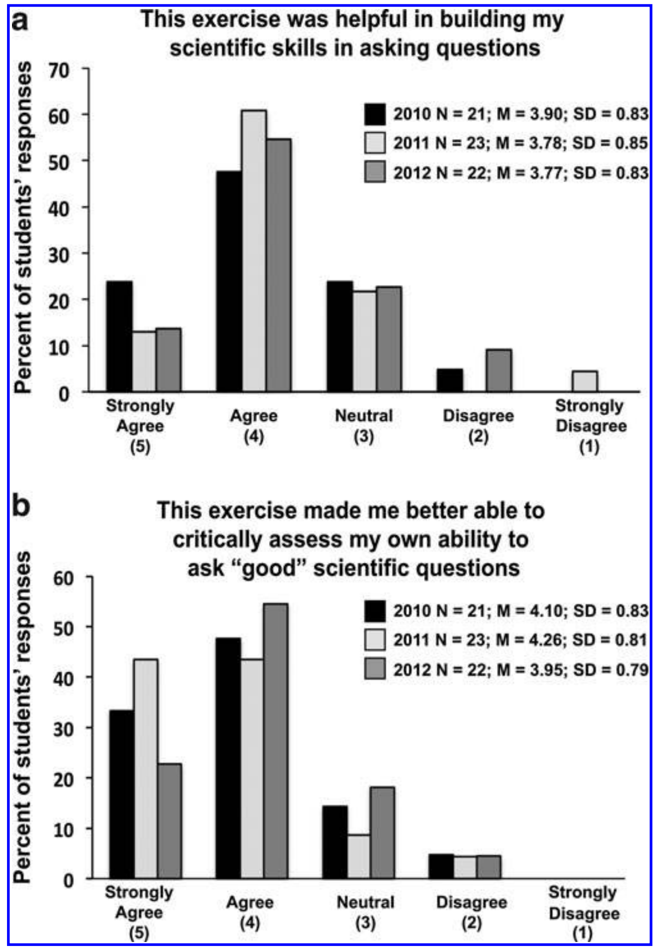

FIG. 3. Post-course survey of students' perceptions regarding the effectiveness of the scientific inquiry exercise with regard to (**a**) building their ability to ask questions and (**b**) improving their ability to critically assess the quality of the questions (N, number of students; M, mean response; SD, standard deviation of responses).

3.3. Students' post-exercise self-assessment of scientific inquiry

Upon completion of the exercise, student opinions were surveyed regarding the effectiveness of the scientific inquiry activity (Figs. 3 and 4). A majority of the students in each year (68–74%) responded that they agreed or strongly agreed that the scientific inquiry exercise was helpful in building their ability to ask pertinent scientific questions (Fig. 3a). Between 22% and 24% of the students were neutral regarding the value of the exercise in building their inquiry skill set, whereas only 4–9% of the students disagreed or strongly disagreed that the exercise was useful.

In addition to their overall perception of the effectiveness of the activity, students were also asked whether the activity helped develop their ability to self-assess the quality and nature of the scientific questions they were asking (Fig. 3b). To help the students develop this ability, students were provided with a series of guidelines during the initial lecture regarding generating and assessing the quality of a scientific question, as described in the methods section. Examples of questions from each category (*i.e.,* ''good,'' ''okay,'' or ''bad'') were presented to the students, and they were asked during the activity to evaluate these examples as well as their own generated questions. After this activity, the post-survey results indicated that the students responded positively to this portion of the exercise, with between 77% and 86% of the students agreeing or strongly agreeing that the activity helped their ability to assess the quality of a ''good'' scientific question. Less than 5% of the students disagreed that their ability to assess the quality of a question was improved, and no one strongly disagreed in the three years the activity was given.

Based on the post-survey results of 2010 and an assessment of the student's responses to the activity, additional questions were added in 2011 and 2012 so that the students' perception of the scientific inquiry activity could be more thoroughly assessed (Fig. 4). Students were asked whether they agreed or disagreed with the statement that they gained confidence in their ability to ask scientific questions (Fig. 4a). In 2011, 48% of the students strongly agreed or agreed

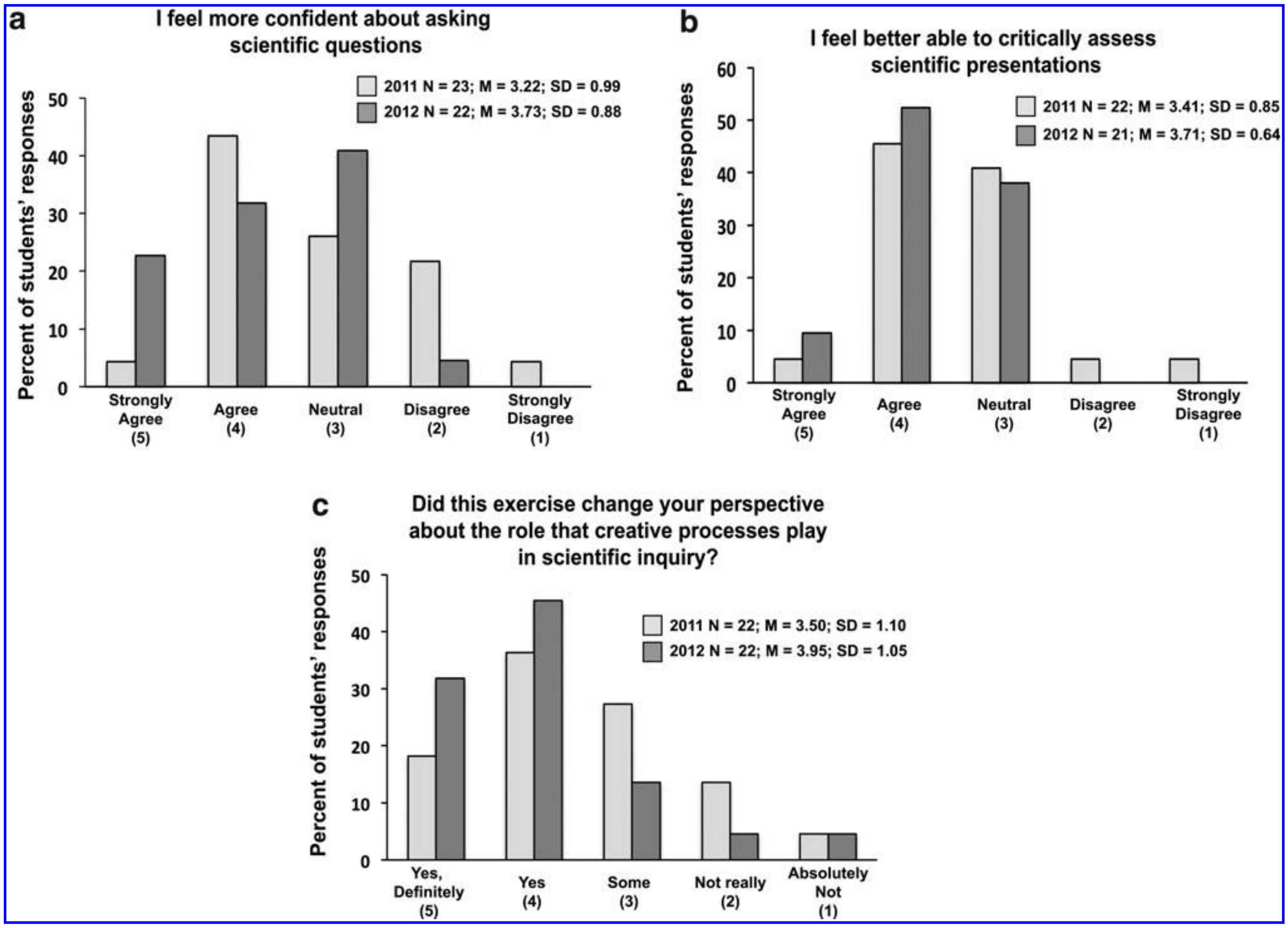

FIG. 4. Post-course survey to assess the students' perceptions on the impact of the scientific inquiry exercise on (**a**) their confidence asking questions, (**b**) their ability to use these new skills in a professional setting, and (**c**) whether the activity changed their perspective on the role of creative processes in science (N, number of students; M, mean response; SD, standard deviation of responses).

that their confidence in their ability to ask scientific questions increased, whereas 26% of the students were neutral regarding the activity, and 26% of the students disagreed or strongly disagreed. In 2012, these numbers shifted slightly, with 54% of the students agreeing or strongly agreeing; 41% of the students were neutral, and only 5% disagreed that their confidence improved.

Students were then asked whether this skill-building activity in general improved their abilities to critically assess scientific presentations (Fig. 4b). The majority of the students agreed or strongly agreed (50–61%) that this activity helped them critique and assess scientific presentations. Between 38% and 41% of the students were neutral regarding improvement in their skills, and in 2011 only 9% disagreed or strongly disagreed with this statement, whereas no one disagreed in 2012. Lastly, students were asked whether their perceptions of the role that creative processes play in scientific inquiry changed as a result of this exercise (Fig. 4c). In 2011, 54% of the students indicated that the exercise changed their perspective of the role of creative processes, whereas 27% of the students thought that the activity somewhat changed their perspective. In 2012, these values increased, with 77% of the students indicating their perspective had changed, whereas only 14% of the students indicated their perceptions only somewhat changed on the role of creative processes in scientific inquiry. Approximately 10–20% of the students felt that their perspective had not changed.

4. Discussion

For students to be successful in astrobiology, they not only require a fundamental understanding of the current state of knowledge in their prospective field but they also require skills to identify potential gaps in that body of knowledge and the ability to explore and close those gaps. In other words, it is not enough for educators to merely teach the answers; we have to teach students how to ask the questions. To promote scientific inquiry learning in the multidisciplinary field of astrobiology, we developed an exercise to help students practice the creative and critical analysis skills needed for generating scientifically oriented questions. Although this was a conventional astrobiology course that targeted the geological and biological basis for Earth's habitability and subsequently the origin of life, this inquiry-based learning module was added to help students better analyze pattern-based data and develop their creative and critical thinking skills. The exercise offers a malleable template that could be modified and adapted for most STEM courses by changing the visual images presented or the podcast content.

The results of students' surveys regarding their pre- and post-exercise perceptions suggest that (1) students feel that they use creative thinking in their science courses, but they are not expanding these classroom experiences to other settings; (2) students can confuse informational- and analytical-based questions and need additional training to self-reflect on the nature and quality of their questions; and (3) the exercise helped increase awareness and appreciation of creativity in scientific inquiry and improved their confidence in formulating and critically analyzing scientific questions.

Although the pre-course surveys strongly indicated that most students use creative thinking skills in their courses, more than half the students surveyed in 2010–2012 indicated that they have minimal or no experience asking scientific questions in a professional setting. These results may suggest that students are too intimidated to ask their questions in these nonclassroom settings. There have been several studies that have examined social influences on students' willingness to share their questions in a group setting, as students are often concerned with potential disapproval of their ideas or questions by their peers or professors (Karabenick, 1996; Pedrosa-de-Jesus *et al.,* 2004). It is often only when one student expresses her or his confusion or questions regarding a subject that other students feel comfortable to discuss their own concerns (Costa *et al.,* 2000). Interestingly, studies on the academic status of students that pose questions in a group setting have shown that average achievers often ask a higher frequency of questions compared to high academic achievers, suggesting that these higher achievers may be more sensitive to potential disapproval of their ideas or questions (Good *et al.,* 1987). Therefore, activities and exercises that can help improve students' self-esteem and confidence in asking questions regardless of their setting are critical.

In addition to the potential intimidation students may feel, the lack of experience asking questions in a professional setting may reflect the overall lack of opportunities that students have had to participate in professional events where they could engage in a scientific dialogue. Student participation in professional events such as scientific conferences and mentored research experiences has been shown to help students increase their awareness of the different scientific fields and feel a part of the scientific community (Hunter *et al.,* 2007). Although there has been a regular call by national organizations and funding agencies to provide more opportunities for student-centered learning to prepare and integrate students into the professional scientific community (National Research Council, 2000, 2003), lack of overall awareness on behalf of the student regarding the importance of these activities in his or her scientific learning process can hamper student involvement in these professional development events. To identify which scenario the students perceived as the reason for their lack of experience asking scientific questions in a professional setting, additional survey questions in future pre-course assessments are required. In either scenario, the results suggest that more efforts are needed to help students translate and apply their classroom experiences to a professional setting.

The scientific inquiry module also revealed that some students appeared to have difficulty differentiating between informational and analytical questions. For example, several students appeared to ask questions regarding how the images or data were generated rather than formulating questions regarding their content or meaning. Informational-type questions were defined to the students as those that provide background information but do not necessarily improve understanding of the materials. Once the guidelines on asking ''good'' analytical questions were provided to the students, some students were able to make the transition to asking more in-depth analytical questions, whereas some were not. The results may indicate that some students are not successfully recalling the information learned in the previous lectures (*e.g.,* metabolisms that promote carbonate mineralization in microbialites) or that this particular exercise was not as effective for some learners. The inability to take prior knowledge that was presented in class and integrate that information into a new context, such as a research seminar, may reflect fundamental differences in the students' learning processes. Some students may not be able to reflect back to earlier lectures and ask ''What do I already know about this topic?'' These self-reflective learning processes, also referred to as metacognition, are more than just study skills; they are key to promoting critical thinking and overall academic success of the students (Adey and Shayer, 1993; Tanner, 2012). The results of the exercises suggest that a more in-depth look at students' metacognitive learning strategies as well as students' concepts of inquiry before and after the exercise are required to fully assess the students' ability to self-analyze their own thinking processes, integrate their prior knowledge, and ultimately begin to think like scientists.

As each classroom and each cohort of astrobiology students will have individualized needs, this exercise provides a malleable template for potential adopters to modify or expand the exercise. For example, an educator may want to alter the podcast component of the exercise to include pre- and post-performance assessments, thereby providing independent measures of students' inquiry skill sets. Also, an educator may want to repeat the activity monthly to continually practice the inquiry skills throughout the course. Regardless, students will require far more training in scientific inquiry than can be provided in a single set of activities; however, this introductory learning module does provide students with fundamental exposure to this aspect of their professional development. Although there are inherent limitations with this self-report, such as using the exercise in a single astrobiology course with the same instructor each year, analysis of the post-exercise surveys from each of the three years the exercise was conducted revealed that student awareness and confidence on the subject did improve as a result of this introductory activity. This positive trend in students' perceptions of scientific inquiry may reflect the in-depth discussions regarding the quality and nature of the student questions. The pre-course surveys suggest that the majority of students are asked to use their creative and scientific inquiry skills in most of their classes, yet in-class discussions revealed that students are not asked to regularly self-reflect on the nature of their questions, which suggests that they do not receive the training and feedback necessary for them to improve and grow in this area. Many times instructors assume students will inherently learn about the nature of science and scientific inquiry by doing science or by listening to seminars. However, studies have shown that students often learn more about the scientific process from debriefings or post-activity discussions regarding what the students have learned or taken away from the exercise (Bell *et al.,* 2003). Again, these results suggest that one learning module cannot convey the full dynamics of scientific inquiry to students, as such activities require incremental steps for students to hone their creative and critical thinking skills. However, as students pursue professional careers in astrobiology, they will continually have to refine these abilities until it becomes second nature to them. Exercises like these scientific inquiry modules can help improve the students' learning experience, increase their awareness of the fundamentals associated with the scientific process, and ultimately help prepare them for a career in science.

Acknowledgments

The authors would like to thank the students of Astrobiology MCB3703 for their enthusiasm and participation in this activity. We also thank Byung-Ho Kang for providing the electron microscopy images that were used in this exercise and Krystal Kerney and Jennifer Larimore for their assistance in collating the student responses. The research used in the learning module was generated through a NASA: Exobiology and Evolutionary Biology Program Element grant (NNX12AD64G) awarded to J.S.F.

Author Disclosure Statement

No competing financial interests exist.

Author Contributions

J.S.F. and J.D.L. conceived of and developed the materials used in the scientific inquiry exercise. J.S.F. taught the course and implemented the exercise. J.S.F. and J.D.L. wrote the manuscript.

References

Adey, P. and Shayer, M. (1993) An exploration of long-term far-transfer effects following an extended intervention program in the high school science curriculum. *Cogn Instr* 11:1–29.

Akin, O. and Akin, C. (1998) On the process of creativity in puzzles, inventions, and designs. *Automation in Construction* 7:123–138.

Bailin, S. (2002) Critical thinking and science education. *Science & Education* 11:361–375.

Bell, R.L., Blair, L.M., Crawford, B.A., and Lederman, N.G. (2003) Just do it? Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching* 40:487–509.

Bloom, B.S. (1956) *Taxonomy of Educational Objectives: The classification of educational goals. Volume 1. Cognitive Domain*, McKay, New York.

Burne, R.V. and Moore, L.S. (1987) Microbialites: organosedimentary deposits of benthic microbial communities. *PALAIOS* 2:241–254.

Chin, C. and Osborne, J. (2008) Students' questions: a potential resource for teaching and learning science. *Studies in Science Education* 44:1–39.

Costa, J., Caldeira, H., Gallastegui, J.R., and Otero, J. (2000) An analysis of question asking on scientific texts explaining natural phenomena. *Journal of Research in Science Teaching* 37:602–614.

Einstein, A. (1916) Die grundlage de allgemeinen relativitätstheorie. *Ann Phys* 49:769–822.

Festinger, L. (1957) *A Theory of Cognitive Dissonance*, Row, Peterson & Company, Evanston, IL.

Foster, J.S. and Drew, J.C. (2009) Astrobiology undergraduate education: students' knowledge and perceptions of the field. *Astrobiology* 3:325–333.

Good, T.L., Slavings, R.L., Hobson-Harel, K., and Emerson, H. (1987) Student passivity: a study of question asking in K-12 classrooms. *Sociol Educ* 60:181–199.

Hake, R.R. (1998) Interaction-engagement versus traditional methods: a six-thousand-student survey of mechanics test data for introductory physics courses. *Am J Phys* 66:64–74.

Hunter, A., Laursen, S.L., and Seymour, E. (2007) Becoming a scientist: the role of undergraduate research in students' cognative, personal, and professional development. *Science Education* 91:36–74.

Hurtado, S., Cabrera, N.L., Lin, M.H., Arellano, L., and Espinosa, L.L. (2009) Diversifying science: underrepresented student experiences in structured research programs. *Res High Educ* 50:189–214.

Karabenick, S.A. (1996) Social influences on metacognition: effects of colearner questioning on comprehension monitoring. *J Educ Psychol* 88:689–703.

Khodadad, C.L. and Foster, J.S. (2012) Metagenomic and metabolic profiling of nonlithifying and lithifying stromatolitic mats of Highborne Cay, the Bahamas. *PLoS One*, doi:10.1371/journal.pone.0038229.

Kolijn, E. (2013) Observation and visualization: reflections on the relationship between science, visual arts, and the evolution of the scientific image. *Antonie Van Leeuwenhoek* 104:597–608.

Likert, R. (1932) A technique for the measurement of attitudes. *Archives of Psychology* 140:1–55.

Mandelbrojt, J. (2006) Similarities and contrasts in artistic and scientific creation-discovery. *Leonardo* 39:420–425.

Mobberley, J.M., Khodadad, C.L., and Foster, J.S. (2013) Metabolic potential of lithifying cyanobacteria-dominated thrombolitic mats. *Photosynth Res* 118:125–140.

National Research Council. (1996) *National Science Education Standards*, National Academy Press, Washington, DC.

National Research Council. (2000) *Inquiry and the* National Science Education Standards: *A Guide for Teaching and Learning*, National Academy Press, Washington, DC.

National Research Council. (2003) *BIO2010: Transforming Undergraduate Education for Future Research Biologists*, National Academies Press, Washington, DC.

Pedrosa-de-Jesus, H., Almeida, P., and Watts, M. (2004) Questioning styles and students' learning: four case studies. *Educational Psychology* 24:531–548.

Pedrosa-de-Jesus, H., da Silva Lopes, B., Moreira, A., and Watts, M. (2012) Contexts for questioning: two zones of teaching and learning in undergraduate science. *Higher Education* 64:557–571.

Root-Bernstein, R.S. (2000) Science in culture. *Nature* 407:134.

Root-Bernstein, R.S. and Root-Bernstein, M. (2013) The art and craft of science. *Educ Leadersh* 70:16–21.

Simon, H.A. (2001) Creativity in the arts and the sciences. *The Kenyon Review* 23:203–219.

Sternberg, R.J. and Lubart, T.I. (1999) The concept of creativity: prospects and paradigms. In *Handbook of Creativity*, edited by R.J. Sternbergs, Cambridge University Press, Cambridge, UK, pp 3–15.

Tanner, K.D. (2012) Promoting student metacognition. *CBE Life Sci Educ* 11:113–120.

Vogt, C.M. (2008) Faculty as a critical juncture in student retention and performance in engineering programs. *Journal of Engineering Education* 97:27–36.

Zion, M. and Sadeh, I. (2007) Curiosity and open inquiry learning. *J Biol Educ* 41:162–168.

Address correspondence to:
Jamie S. Foster
Department of Microbiology and Cell Science
University of Florida
Space Life Science Lab
Merritt Island, FL 32953

E-mail: jfoster@ufl.edu

Submitted 30 August 2014
Accepted 17 October 2014