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Beyond Exhibits: Exploring Bio-Inspired Education Robots in Museums for STEM Enrichment

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Over the past few decades, there have been national calls to improve science, technology, engineering, and mathematics (STEM) education and bolster the STEM workforce, with more recent calls to advance diversity within STEM [1]. Formal education opportunities within K12 and post-secondary education are one area that can engage students in STEM. In addition to formal schooling opportunities, informal STEM learning can bolster interest in and engagement with STEM [2], [3]. Museums are a common setting for informal STEM learning opportunities [4], [5]. Robots also show promise to pique students' interest in STEM and be used as a pedagogical tool in both formal and informal educational settings [6], [7], [8].

In this study, we evaluate the efficacy of a bio-inspired educational robot (BIER) in enhancing biology and engineering learning in informal educational settings. The research team developed a bio-inspired educational robot that simulated a reticulated python's jaw – or a snake jaw robot. The robot aimed to promote integrated STEM learning, including the physics concepts of links, joint range of motion, and how snakes manipulate their jaws to eat. The research team shared the snake jaw robot with a museum of nature and science in the northeastern United States. We were particularly interested in how the museum might implement the snake jaw robot in an informal STEM learning environment. The following research question guided this study: ***How and in what ways do staff members envision using the snake jaw robot in the museum?***

Related Literature

Integrated STEM Learning

Integrated STEM learning combines two or more STEM subjects into a joint learning experience, which can help learners draw connections across disciplines [9]. Moore et al. [10] emphasize that while one subject can be the main focus of a lesson, integrated STEM learning practices will incorporate ideas and concepts from multiple disciplines.

Prior research demonstrates the efficacy of integrated STEM learning. First, integrated STEM learning can help students draw connections across disciplines. It also enhances students' problem-solving skills [9], [11]. Other studies found that integrated STEM learning practices can improve STEM literacy, STEM workforce readiness, and cross-disciplinary connections [12], [13], [14]. While there are mixed results on the benefits of integrated STEM learning on student achievement, there is still compelling evidence suggesting that continued STEM integration teaching can advance student learning [15]. Across K12 education, the Next Generation of Science Standards (NGSS) calls for students to make deeper connections across STEM disciplines. Integrated STEM education is one possible pedagogical approach to advance these connections for students.

Museum Settings

Museums are ideal for facilitating informal learning opportunities [16], [17]. This does not imply that museums are not formal organizations with clear goals, structures, and practices but that they are ideal settings for learning to occur in an environment different from traditional schooling [18]. Museums, which are designed physical spaces, can help facilitate students' learning in more open-ended and exploratory ways [18], [19].

Museums can be an important place to foster STEM-based conversations for students (with other students, teachers, families, and friends), which can promote further STEM interest [4], [20]. Research also demonstrates that museums help cultivate scientific and critical thinking skills for students [21]. Further, museums can help foster student interest in science and student achievement [21]. Ultimately, museums are essential environments to promote informal learning opportunities and potential STEM interest and understanding for students.

Bio-Inspired Educational Robots

Research demonstrates that educational robots can foster interest in STEM-related topics [6]. Further, educational robots can also encourage integrated STEM learning [22]. A broad range of robots have been used in academic settings, including Legos © [23], Artbotics [24], and TangibleK Robotics [25]. Most robots in educational settings have been used to teach engineering, programming, and design. Along with calls from NGSS to foster greater interdisciplinary STEM learning, researchers and teachers have begun exploring the use of bio-inspired educational robots (BIERs).

BIERs, which came out of bio-robotics, construct robots inspired by biology [26]. These robots can look like animals, such as fish, snakes, or other animals. BIERs are an ideal technology to promote integrated STEM learning [26], [27]. A significant challenge with many BIERs is they are expensive and difficult to construct, use, and replicate for educational purposes [28]. There is a need to develop low-cost, easy-to-use BIERs to help facilitate integrated STEM learning, especially within multiple learning environments.

Conceptual Framework

This study was guided by constructivism as a learning theory. The works of early scholars, including Piaget [29], Brunner [30], and Vgytosky [31], helped form our contemporary understanding of constructivism as a learning theory. While no single agreed-upon definition exists, constructivism posits that learning is a process whereby people construct meaning and make sense of their experiences [32]. Vgytosky's [31] work formed the basis for social constructivism, which emphasizes that individuals learn within the context of cultural, historical, and other social interactions, which all help shape our understandings.

Hoover [33] established principles for people to use when teaching with a constructivist approach. First, he posits that learners use existing knowledge in their learning processes; past knowledge influences current learning. Next, Hoover argues that learning is not a passive process whereby we impart knowledge to students. Instead, they are active participants in their learning processes. Murphy [34] synthesized a set of characteristics and teaching/learning practices from the literature. First, constructivism assumes that we all have unique perspectives; thus, there are multiple perspectives and representations of different concepts or learning topics. Further, activities should encourage individuals to participate in learning processes of self-analysis and self-reflection. One of the best ways to facilitate this process is to foster learning environments that emphasize the "real world" through relevant and authentic practices. Littleton [35] highlights the relevance of Murphy's principles within museum settings as an ideal place to foster constructivist learning.

Stemming from constructivist theory, active learning is a pedagogical approach that centers students on learning by engaging them in interactive practices [36]. Active learning comprises a broad range of pedagogical practices, from initiating student-to-student discussions, integrating real-world applications in class, facilitating group activities, using formative feedback, asking students to lead activities, and many other potential learning activities. The important part of active learning is engaging people directly in the learning process so they actively participate in their knowledge acquisition. There is a broad body of knowledge emphasizing the efficacy of active learning over traditional, instructor-centered practices [37], [38], [39]. Active learning can increase student engagement in the learning process. Within STEM disciplines, active learning can improve student achievement outcomes.

Methods

Study Context

The setting for this study was a museum of nature and science in the northeastern United States. The museum was founded in 1957. The museum has been open to the public since 1975 to serve as a public and informative space to serve the general public. The museum aims to ignite a life-long passion for learning about nature and science. The galleries and rotating exhibits help guests explore how we are all connected through dynamic and diverse ecosystems.

The museum comprises seven departments: business operations and guest experiences; collections and research; communications; development and membership; exhibits; facility operations; and public engagement. The public engagement department includes nine full-time employees working to develop strategies, exhibits, programs, and other educational experiences for the museum guests to enjoy and learn about nature and science. The public engagement department is responsible for the educational programs offered by the museum, including summer camps, school tours, community outreach visits, and other initiatives. They also develop educational content within the museum. In this study, we shared the snake jaw robot with the public engagement team at the museum so they could use it in various educational programs.

In the summer of 2023, the research team met with the public engagement team at the museum to introduce them to the snake jaw robot. This meeting lasted 2 hours and functioned as a training and point of observation. The designer of the robot, one of the researchers, presented the snake jaw robot to the group. The other researcher attended the meeting virtually to observe the session. They demonstrated the robot in this part and then told them how to use it. In the next part of the meeting, the director of the public engagement team led the rest of the staff in a discussion about how they envisioned using the snake jaw robot in the museum.

Robot Design

The snake-jaw robot was designed to illustrate the physiological function of the quadrate bone unique to snakes, enabling them to consume their prey. Many museums conduct routine programs where visitors witness live snakes being fed. However, educators are generally limited to using images, animated videos, or static snake skulls to describe the biological phenomena – specifically the kinematics and dynamics of the snake jaw. Although live feeding is exciting, the biological phenomenon is hidden under the snake's skin. Additionally, the museums cannot offer live feeds to all visitors or even daily due to the low frequency at which snakes consume food. Therefore, there was a need for a robot that could accurately mimic the biting and chewing motion of the snake jaw and be used to explain the function of the quadrate bone while being interactive, hands-on, and engaging for the audience.

The robot consists of a base to house the electronics, support rods to suspend the snake jaw, the skeletal components of the snake jaw, four servo motors to actuate the jaw, a microcontroller, a battery, and the essential wiring (Figure 1). The skeletal components of the snake jaw include the skull, left and right quadrate bones, left and right lower mandibles, and the inner teeth. The structural elements of the robot are 3D printed, and the electronics can be purchased readily through online retailers like SparkFun and Amazon. The snake's jaw can be assembled in less than 60 minutes, and the parts cost less than $60, assuming the availability of a 3D printer. The jaw is lightweight and compact for portability and easy storage. The assembled jaw is approximately 12" long, 12" wide, and 15" tall, allowing multiple learners to observe and interact with it. The jaw does not need to be plugged into a wall. The kinematics of the jaw can be controlled using a free software application (Figure 2). The jaw fully opens by moving the lower mandibles down, the quadrate bones back, and the skull up. The jaw closes by moving the lower mandibles up, the quadrate bones forward, the skull down, and the quadrate bones back again. The software gives the users multiple modes to actuate the jaw (as described below).

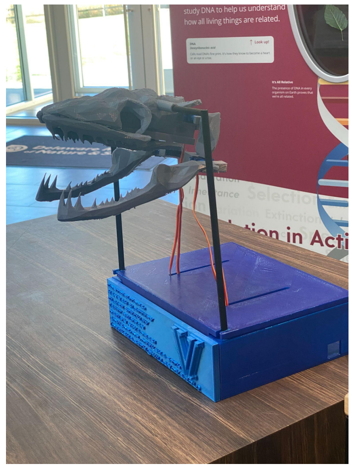

Figure 1. Snake Jaw Robot.

1. Strike - opens and closes the jaw within 4 seconds
2. Open - spreads the jaw and pauses there, giving educators some time to discuss the learning objectives
3. Close - closes the jaw
4. Stepper - each side of the jaw turns opening and closing to mimic how the snake swallows the prey after striking.
5. Slow motion - opens and closes the jaw at half-speed
6. Comparison mode - the jaw actuates as if the snake didn’t have a quadrate bone to visually show the difference in the range of motion that the unique quadrate bone causes.

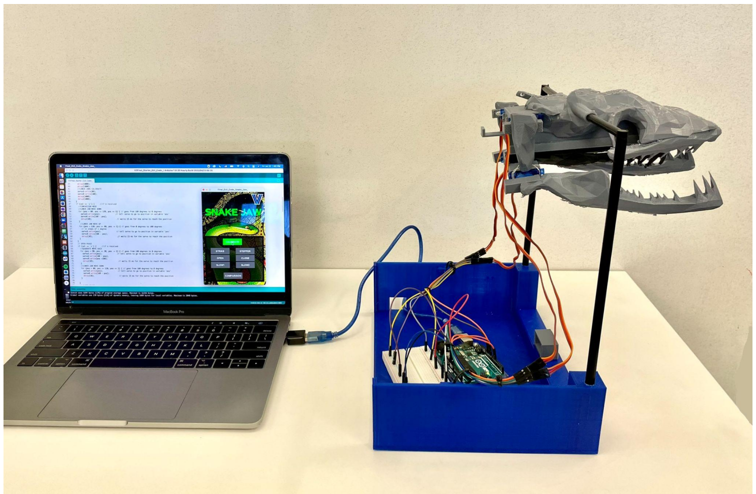

Figure 2. Snake Jaw Robot with Computer Set Up.

Data Collection & Analysis

Multiple sources of qualitative data collection informed this study. The training session and subsequent conversation with museum staff (n=7) were used to collect initial thoughts about how to use and reactions to the snake jaw robot. Next, a subset of the museum staff (n=5) participated in an interview a few weeks after the focus group. The timing of this follow-up interview allowed the staff members time to reflect on the snake jaw robot in the museum. The training session and individual interviews were all recorded and transcribed via Zoom. The transcript was then reviewed and corrected. Data were then de-identified. The transcripts were then uploaded and analyzed using HyperResearch software. See Table 1 for a summary of the participants (pseudonyms are presented here to preserve anonymity).

Table 1. Participants

Name	**Title**	**Gender**	**Participation**
Jennifer	Director	F	Training & interview
Phil	Interpretation Lead	M	Training & interview
Marissa	School Program Manager	F	Training & interview
Charlotte	Special Events & Program Manager	F	Training & interview
Paige	Intern	F	Training & interview
Brad	Discovery Gallery Coordinator	M	Training
Sofia	Early Childhood Program Lead	F	Training

Following Creswell's (2009) steps, we utilized an inductive approach to code the qualitative data to determine themes and subthemes [40]. In the first round of analysis, we used in vivo coding [41], where I took participants' words to create broader categories. I then went back through and used code mapping to wrap these initial codes into three broader themes [41]: potential instructional uses, tangible examples, and interdisciplinary connections.

Results

Potential Instructional Uses

Staff members discussed multiple ways to use the snake jaw robot in the museum. They shared several ideas, spanning both formal and informal presentations.

During the training session, all staff members thought that the snake jaw robot in the Discovery Gallery would be beneficial. Phil described the Discovery Gallery as "designed to be like a hands-on interactive space for ages eight and up. So, all the activities in that section of the museum are hands-on stuff they interact with. It's also meant to change, so it's one of the parts of the museum that changes regularly, especially for our guests who are regular returning members." Within the Discovery Gallery, Charlotte described that the museum hosts "pop-up science programs throughout the day. Essentially, one of our staff members does a 15- to 20-minute presentation, demo, or activity. And then one of our staff members puts their spin on it" with their expertise. Charlotte used the snake jaw robot in one pop-up program between the training session and her interview. She said people saw the snake jaw robot and were curious about what it was, so that drew them over. Overall, she felt using the snake jaw robot in the pop-up went well.

Several staff members mentioned using the snake jaw robot to complement presentations with their live snakes. Phil also discussed plans to use the snake jaw robot in a pop-up program involving a live animal feeding with the museum's snake, "Jake." Charlotte had a similar idea: "One idea is to pair it [the snake jaw robot] with a live feeding of one of our snakes. That is a nice, easy one to do." Marissa echoed this idea, "So I was thinking we could add that to when we do our live animal presentation as part of that. If we use a snake we can the snake jaw there to kind of talk about how they work together." The staff tried the live snake demonstration, which was met with a lot of enthusiasm from guests (see Figure 3). Ultimately, having a live snake and the snake jaw robot at the same presentation could expand guests' understanding of how snakes eat, their anatomy, and other topics.

Figure 3. Live Snake Demonstration.

Multiple people mentioned connecting the snake jaw robot to the Next Generation Science Standards (NGSS). Jennifer, whose role requires her to focus on big-picture ideas with the museum, talked about the importance of connecting what happens in the museums with science standards. She explained that when they "are talking to teachers and getting them to come here for programs, a lot of teachers or administrators won't give permission to come here unless we meet standards. So to be able to meet standards and to be able to teach concepts using the snake jaw robot will be made better and clearer." Jennifer felt the snake jaw robot would help connect to NGSS science standards.

On the other hand, Marissa's role is more closely tied to directly developing programs for schools and the community. In her interview, Marissa also talked about how to use the snake jaw to connect to NGSS. Regarding one particular standard, she shared that "one standard is all about the body systems and how they work together. And so I was taking a look at the specifics and the boundaries of that assessment. So it specifically says it's limited to the circulatory, expiratory, digestive, respiratory, muscular, and nervous systems. And in that, I could see talking about the muscles, I can see talking about the nervous system, skeletal, digestive, and even respiratory. Because even though you are thinking about how they are consuming, you can talk about how do they breathe with this giant bolus in their throat. So, I am already working on a program with educators about how to specifically cover this for middle school students." She mentioned a few other standards and ways to use the snake jaw to facilitate learning of that particular standard. Marissa also shared that the museum could use the snake jaw robot to facilitate conversations with kids. For example, she asked questions like, "What do you guys notice? What do you wonder?" She explained that those are big talk words with NGSS standards and curriculum - notice and wonder." Ultimately, staff members felt that the snake jaw robot would facilitate connections with NGSS in the museum.

Tangible Example

In the initial training session, staff members shared excitement about the potential of the snake jaw robot as an instructional tool. They mentioned a few benefits of the snake jaw robot but were mainly focused on *how* they planned to use the robot in the museum. However, during the interviews, every staff member discussed the benefit of having a tangible, physical example of the snake jaw robot.

When they brought up the benefit of the physical snake jaw robot, every person made a motion of how a snake eats with their hands. They would bring their hands together and then open them like a hinge at the palms. Each person said that this was a common way they might approach or describe snake eating. Jennifer said, "And using something like this is much easier than us having to go like this [uses hand motion]. And you know, using those analogies." Phil affirmed this idea, saying, "And here we have an easy demonstration piece to show people, instead of me just [moves hands] like doing weird stuff with my hands." Charlotte mentioned that the robot's design helped facilitate this process. She explained, "It is big, it is very visible, so it's eye-catching. And that it actually moves. I think it is one of the biggest benefits. So it's not just us standing there with a big skull doing this [motions unhinging the jaw] like, you can actually see it essentially in real-time." Ultimately, the snake jaw provided a clear visual that the museum staff could use to explain concepts to guests. The museum intern, Paige, suggested personalizing the snake jaw robot. She explained, "It'd be cool if they made a profile of it. Like, you can name it or something. And then, what does it like to eat? … Make it individualized. Having more of a connection with them."

Jennifer described that in current practices (before the snake jaw robot), if the museum presented a lesson (or activity, or pop-up) on how snakes eat, they would have to describe what happened. She said, "So for us to say to kids, can you imagine opening your mouth and having your jaw drop down and open up, and you can take a whole watermelon all the way down, right? So that's a lot of imagination to go into for a young kid." This process was difficult for guests to picture. Jennifer talked about the benefit of the snake jaw robot to guests' understanding: "So this was a way to make that connection with guests and have it even more accurate because we can't control what people are taking away from our words and our hand gestures in our word pictures. But now we've got this physical object that actually does what we're saying, that makes sense." The BIER would give kids something to see in the museum. They could visually interact with the snake jaw robot and touch it. Seeing how the snake jaw moves would be a good starting point for the museum staff to use with kids.

Interdisciplinary Connections

Many people talked about the potential for the snake jaw robot to facilitate integrated STEM learning through interdisciplinary connections. They discussed ways the snake jaw robot could span multiple disciplines, such as science, biology, engineering, computer science/programming, and robotics.

Phil emphasized that the snake jaw robot is versatile; he stated, “It’s not just biology that we can talk about with this resource.” He describes the robot as “an interdisciplinary piece of equipment and an interdisciplinary resource,” which allows for “ a lot of opportunity.” Both Charlotte and Phil mentioned that the snake jaw robot could be used to facilitate lessons on 3D printing. Charlotte said that the snake jaw robot “is a great example of what you can do with a 3D printer.” Phil affirmed this idea and expanded on it, “we can also talk about the manufacturer, we can talk about 3D printing, we can talk about that modeling computer program.” Phil also talked about letting kids look at the code to manipulate the robot and then using that as a springboard for a programming camp or robotics club.

Staff also described multiple disciplines that could be enhanced using the snake jaw robot. Charlotte said, “I think it’s a really great combination of the robotics and biology aspects. I thought it was really just a great combination of both of these.” Upon initial examination, the snake jaw robot could easily be used to facilitate the discussion of robotics and biology. But the staff also thought of many other possibilities. Marissa said, “I think it has some good connections for neurology. You could also talk about what happens when a snake eats live prey - or their physical and chemical changes.” Marissa described another possible use, “we have a home sweet home habitat, which is all about habitats - so water, food, air, shelter, and space.” Charlotte also mentioned using the snake jaw robot to facilitate discussions on anatomy, “We have a lot of skulls here from all sorts of animals, and this one actually having it where it is a bigger version is really gonna complement.” Ultimately, staff envisioned using the snake jaw robot to broaden students’ understandings across multiple disciplines.

Discussion & Conclusion

The findings from the qualitative data indicate that the snake jaw robot is a strong technological tool for use in the museum setting. During the initial training session, staff seemed excited by the pedagogical opportunities to use the museum's snake jaw robot. This conversation not only showed excitement about creating new educational programs with the BIER, but they also demonstrated a mastery of pedagogical practices. They all mentioned multiple ways to use the robot and connected it to the NGSS pedagogical needs. During this meeting, the staff already had numerous ideas about using the robots in various settings, including formalized school and informal pop-up science programs in the Discovery Gallery. The staff members have different educational backgrounds, including engineering, biology, and science education. As such, they also talked about a broad range of potential interdisciplinary applications, including biology, engineering, computer science, robotics, and other STEM subjects.

A few weeks after the training, we met with the staff individually for interviews. During the discussions, we discussed how they had used the snake jaw robot or any plans they had to use it. In every interview, staff members mentioned that the snake jaw robot was helpful because it provided a tangible, visual example of a snake jaw. They also all noted that the robot would be (or had already been) helpful when teaching snake jaw mechanics because they did not have to use their hands but could instead point to different jaws, demonstrating how the reticulated python's jaw worked. Each person mentioned this was a crucial feature to help enhance guests' learning and accurate understanding of the snake jaw and how snakes eat.

During the training, people mentioned informal and formal learning settings to use the snake jaw robot, which varied depending on the areas that people oversaw. Some people, particularly Jennifer and Marissa, were enthusiastic about using the snake jaw robot in formalized school programs - mainly field trips. Both of their interviews discussed ways the snake jaw robot can connect with various objectives specified by NGSS. For instance, Marissa shared ideas about using questions such as what people "notice" and "wonder" about the snake jaw robot. They both felt that the snake jaw robot could be a helpful tool to advance teachers' work at expanding students' STEM knowledge. At the time of the interviews, neither Jennifer nor Marissa had formalized any plans to use the snake jaw robot with the school programs.

Phil and Charlotte expressed excitement about using the snake jaw robot in the more informal *Discovery Gallery* space in "pop-up" science programs. For these programs, staff members put their own "pin" on the mini-lessons or demonstrations presented depending on their expertise. As such, each person could use the snake jaw robot differently while connecting it to different disciplines. Charlotte used the snake jaw in a biology lesson, which she said went well. Guests were intrigued by the snake jaw robot - and she felt it enhanced their understanding. Phil had plans to use the snake jaw robot in connection with a live feeding of the museum snake. Both mentioned wanting to use the snake jaw robot to facilitate discussions about 3D printing and robotics.

This study has a few limitations. First, the study was conducted with a few staff members at one museum. We only collected feedback from museum staff during the ideation and preliminary planning phases. Further research needs to be conducted to see how the staff use the snake jaw robot long-term. This can better inform planning for formalized school programs. With more time, we expect to see several interdisciplinary lessons to promote integrated STEM learning. Further research can help us determine how well the snake jaw robot worked. Additional research should also be conducted to see how formal education settings like school classrooms can integrate BIERs to encourage integrated STEM learning.

Ultimately, the snake jaw robot was viewed as a tool to facilitate multiple learning opportunities for kids, ranging from elementary to high school students, across various subjects. These conversations with museum staff showed promise for using the snake jaw robot as a pedagogical tool in an informal setting. These preliminary findings demonstrate a promising potential for using the snake jaw robot and other BIERs to promote integrated STEM.

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