Different Sub-Domains of Biology May Be Influencing Practices in Simulated Authentic Science Inquiry

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Table of Contents

Introduction

According to the National Center for Science and Engineering Statistics (2023) between the years 2011 and 2021, the STEM workforce grew from 29 million to 34.9 million. The United States Department of Labor Statistics (2022) estimated that this total is projected to grow by approximately 10% in the next ten years. Given the rapidly growing demand for STEM jobs, there is also a need for more STEM professionals to fill these roles. However, retention rates of students pursuing a STEM degree are low, with 40% of individuals who enter college declaring with a STEM major actually graduating with a degree in STEM fields (President's Council of Advisors on Science and Technology, 2013). Researchers coined the term “the leaky pipeline” to describe this problem. More specifically, women and in particular, women of color are susceptible to attrition out of STEM fields (Calhoun et al., 2022). Many hypotheses exist for the inability to retain women in STEM, spanning from systemic biases to lack of mentorship (Calhoun et al. 2022). However, one study says that this phenomenon could be due to poor science education experiences (Sithole et al., 2017). With a growing demand in STEM jobs, it is important for researchers to understand why these students are leaving the stem field and how educators can adapt to allow for higher retention rate of STEM graduates.

The study of epistemological beliefs about science (EBAS), or the study of science knowledge and what it means to “know” something is scientific is integral to science education. For instance, it shapes how students understand and engage with scientific knowledge. A lingering question in the field that will shape how we teach EBAS, is whether or not EBAS are discipline specific. For example, in 2008 DeBacker and colleagues demonstrated that EBAS are context dependent and hypothesized that each discipline of science has its own distinct inquiry. There are also very few studies exploring EBAS at an undergraduate level. Of these studies there are very few in the context of biology, and no study looked at EBAS in different subdomains of biology. How do we effectively teach EBAS to undergraduate biology students? What do we know about life science major EBAS? To answer these questions, my honors thesis project examined how undergraduate EBAS as seen through SCI practices vary as the result of subdomain of biology.

Epistemological beliefs about science

Epistemological beliefs about science are beliefs an individual has regarding science knowledge and how an individual acquires this knowledge. Researchers established four dimensions of scientific epistemological beliefs: source, justification, certainty, and structure (Hofer and Pintrich 1997). Source refers to beliefs about where scientific information comes from. For example, if someone says "My mother says the influenza vaccine is not safe, so I won't get one" it demonstrates that a parent is more valid source of information than a public health organization, like the Centers for Disease Control. Justification is how an individual uses evidence to support their claim. For example, using various to studies to back up the claim that antibiotic resistance in bacteria is driven by natural selection and evolutionary processes. Certainty refers to beliefs about how scientific knowledge changes over time. For example, the structure of the atom has changed with new scientific studies. Structure is how an individual's beliefs progress or evolve. For example, a high school student saying "science is just a bunch of facts I have to memorize" and then later understanding how science is a process that solves problems in society.

When assessing EBAS often researchers identify beliefs as sophisticated or unsophisticated. Sophisticated epistemological beliefs about science are beliefs that involve the understanding the complex and tentative nature of science knowledge. For example, someone with a more sophisticated understanding of certainty would suggest that scientific knowledge changes in light of new evidence. Less sophisticated epistemological beliefs about science are beliefs that often involve oversimplifications of how scientific knowledge is generated. For example, someone with less sophisticated understanding of certainty would suggest that once scientists know something we know it forever. One goal of science education is to facilitate the development of more sophisticated EBAS. However, we do not know what the best methods are for doing so, and how EBAS focused instruction could be used to improve science education and ultimately improve STEM retention rates.

Authentic science inquiry

Researchers define authentic science inquiry as providing students the experience "of what scientists 'do', how science is done, and what science 'is'" (Rowland et al. 2016). Simple science inquiry usually involves straightforward investigations with clear outcomes. For example, a common experiment used in elementary schools is determining if the amount of sunlight will affect plant growth. Authentic science inquiry, on the other hand, delves into more intricate scientific questions that requires more sophisticated experimental design that either has a non-obvious answer, multiple solutions, or lacks a clear solution. Authentic science inquiry provides students with firsthand experience in the practice of science which allows a deeper understanding of the nature of science knowledge. Examples of authentic science inquiry for students include exposure to course-based undergraduate research experiences, CUREs (Auchincloss et al. 2014; Corwin et al. 2015) or simulated authentic science inquiry such as SCI simulations (Peffer et al. 2015). SCI is best characterized as a conceptual simulation (Renken et al. 2016) because it models authentic science inquiry by providing structural support while allowing autonomy for the participant. SCI is an authentic experience because it engages individuals to participate in unstructured real-world problems. Although this simulation exists on a computer, it contains many elements of authentic science inquiry.

Science Classroom Inquiry Simulations

Science Classroom Inquiry (SCI) simulations allow for authentic science inquiry that can be observed and analyzed through technological means. For example, what students do in SCI reflects a participants EBAS. For example, how individuals discuss their results can be used to examine their certainty. In Peffer and Kyle (2017), the authors demonstrated that individuals with more experience in authentic science inquiry were more likely to use hedging language in their conclusion, which may reflect beliefs regarding the certainty of scientific knowledge. In addition, what information an individual utilizes could indicate beliefs about the source of scientific knowledge. Individuals using data within the simulation to support their claims is an example of justification. How individuals discuss their results can be used to examine their certainty. Development can be studied by seeing how an individual's interpretation of the problem changes when new data is presented.

The majority of previous SCI simulations model ecological scenarios. For example, the 2015 *Unusual Mortality Events* simulation put students in the place of a marine biology, trying to understand historic mass death events effecting pelicans, manatees, and dolphins along the eastern coast of the United States (Peffer et al. 2015). The *Invasion of the Grackles* Simulation, used in this study, asks students to evaluate why a nuisance bird species, the Great Tailed Grackle, is expanding its range (Peffer et al. 2020).

EBAS Assessments

Creating evidence-based interventions around EBAS in science education requires ways to assessing students' EBAS. Despite the importance of EBAS, methods of assessing EBAS are woefully lacking. A limitation of the current assessments of epistemology is that assessments are taken at one fixed point in time and do not reflect changes in understanding over time. Assessments that force individuals to make a choice assume that participants can be put into categories that match the philosophical beliefs of the survey authors (Sandoval 2005; Sandoval and Redman 2015). These assessments often use Likert scale metrics, which researchers have criticized for their lack of reliability and validity (Sandoval et al. 2016). One possible solution to these challenges is to examine student practices in real time. Peffer and colleagues demonstrated that experts and novices, as defined by their experience with authentic science practices, have distinct practices in SCI simulations. Furthermore, Peffer and colleagues concluded that the use of practices in simulation authentic science inquiry could be used as a proxy for student's epistemological beliefs (Peffer and Ramezani, 2019, Peffer et al. 2020).

Materials and Methods

Participants

Participants for this study (n=38) were undergraduate life science students enrolled at a large public research university. All participants were all enrolled in first semester introductory biology courses. 63% were female, 34% male, and 3% nonbinary. The predominant ethnic group was Caucasian (71%). Most participants were freshmen (81.5%). The distribution of majors was diverse: 25% molecular, cellular, and developmental biology majors, 13% neuroscience majors, 5% integrated physiology majors, 5% biomedical engineering, and 5% psychology majors. Between the two test groups the demographic distribution was statistically equivalent.

Data collection and analysis

All data was collected online via Zoom during a single meeting for each participant that lasted approximately an hour. Since factors like self-efficacy and motivation can influence EBAS, participants first completed a pretest that assessed these factors using the Motivated Strategies for Learning Questionnaire (MSLQ) (Pintrich et al., 1991) and the Colorado Learning Attitudes about Science (CLASS-Bio) (Semsar et al. 2011). The pretest took participants approximately 30 minutes to complete.

The MSLQ measures student's learning strategies and motivations to learn biology. The motivation subscale consists of intrinsic goal orientation, extrinsic goal orientation, task value, control beliefs, self-efficacy, and test anxiety. The learning strategy subscale consists of rehearsal, elaboration, organization, critical thinking, metacognition, time and study environment, effort regulation, peer learning and help seeking. The MSLQ was coded as described in the scoring manual and a mean score for each subset was calculated. The average values of each subset were compared for the group of individuals that took *Invasion of the*

Grackles vs the group that took *Cracking the Next Pandemic* simulation and a T test was performed to determine any statistically significant differences between the two participant pools (α=0.05).

The Colorado Learning Attitudes about Science Survey (CLASS-Bio) was used to measure learning attitudes about science. Participants were given statements and then asked to rate each item on a 5-point Likert scale from strongly disagree to strongly agree. The average values of each subset were compared for the two datasets and an independent T test was performed to determine any statistically significant differences between the two groups (α=0.05).

Following the pre-test, students completed an ecology-based simulation, *Invasion of the Grackles* SCI simulation (Peffer et al. 2020) or a new molecular biology simulation called *Cracking the Next Pandemic*. Participants were assigned to each simulation randomly. In each simulation, participants were given an authentic science problem and asked to investigate potential explanations for a phenomenon.

After introduction to a real-world science problem, participants could look for background information using the library, run tests, generate new hypotheses, and make conclusions. Nineteen participants completed *Invasion of the Grackles* while 19 participants completed *Cracking the Next Pandemic.* Participants completed *Invasion of the Grackles* in an average of 29.12 minutes, whereas participants completed *Cracking the Next Pandemic* in an average of 34.8 minutes.

The SCI simulation application captured both responses written by students in their notebooks and their clickstream data. Clickstream data is a record of actions users take online, like clicks, page views, and form submissions. A screen recording also captured the participants' actions in real time. All actions were coded as described in Peffer et al. 2020. Investigative actions were defined as hypotheses generated and tests performed (Table 1). Information seeking actions were defined as reading information from the library embedded in the simulation and using the internet to search for additional knowledge (Table 1). Total actions were defined as the number of investigative actions plus the number of information seeking actions (Table 1).

Type of Action	**Definition of Action**
Information Seeking Action	Reading information from the library embedded in the simulation and/or using the internet to search for additional knowledge.
Investigative Action	Hypothesis generated and tests performed.
Total Actions	The number of investigative actions plus the number of information seeking actions.

TABLE 1. Types of Actions and their definitions.

Each participant's investigation was coded by two people as simple or complex. The simple and complex categorization is based on China and Malhotra's definition of simple or complex inquiry, and in line with previous work by the Peffer lab (Peffer and Ramezani, 2019, Peffer et al. 2020). The parameters of a simple investigation were defined as a participant performing a few tests until a basic cause and effect relationship led them to draw a conclusion. A complex relationship was one in which a participant completed a multi-pronged investigation that uncovered multiple cause and effect relationships. The interrater reliability between the two coders was 76.3%. All disagreements were resolved through discussion.

To avoid potential stereotype threat, participants completed a demographic survey upon completion of the simulation.

Results

Development of a new molecular biology SCI simulation

SCI simulations have informed researchers about EBAS in ecology scenarios, however other subdomains of biology remain unstudied. Since EBAS may be context dependent (DeBacker et al. 2008), it is important to study EBAS between the subdisciplines of biology. This gap in knowledge led to the development of a novel lab based molecular biology simulation *Cracking the Next Pandemic*.

Cracking the Next Pandemic simulation was developed based on the introductory molecular biology sequence at the University of Colorado Boulder, MCDB 1150 (introduction to molecular, cellular, and developmental biology) and MCDB 2150 (principles of genetics) curricula. The tests were chosen and designed based on common laboratory techniques used by molecular biologists that the student population we recruited from would be familiar with. For example, one test allows participants to examine a western and southern blot and interpret the results.

In *Cracking the Next Pandemic,* students are asked to characterize and determine the function of an unknown protein. Different tests allow them to examine the proteins shape, size, and location within the cell. This simulation had nine tests available to participants. It also included a library embedded in the simulation that allowed participants to search for information.

The molecular biology simulation was beta tested with thirteen individuals, in Spring 2021, all who were enrolled in MCDB 2150 Principles of Genetics. These individuals provided immediate feedback about the simulation and small adjustments were made before it was launched for data collection. For example, we added more information in the library section of the simulation.

Survey metrics indicate no baseline differences between participants.

Since non-epistemological factors could influence simulation practices, we first examined the baseline differences between groups. We observed no difference in the majority of motivation subscales between the two populations. However, there are a few significant differences between the groups in the peer learning $t=4.66$, $P < 0.03$, help seeking $t=5.05$, $P < 0.03$, and time and study environment subscales $t=5.68$, $P < 0.04$ (Table 2).

	Participants who took Invasion of the Grackles	**Participants who took Cracking the Next Pandemic**	**P value**
Motivation Subscales			
Intrinsic goal orientation	5.25 (0.83)	5.59 (0.70)	0.18
Extrinsic goal orientation	5.5 (1.00)	5.32 (0.74)	0.46
Task value	6.16 (0.89)	6.03 (0.77)	0.64
Control beliefs	5.45 (0.71)	5.85 (0.82)	0.12
Self-Efficacy	4.97 (1.22)	5.33 (1.07)	0.35
Test Anxiety	5.00 (1.32)	4.64 (1.42)	0.44
Learning Subscales			
Rehearsal	4.43 (1.07)	3.93 (1.50)	0.25
Elaboration	5.18 (0.63)	4.80 (0.94)	0.16
Organization	4.92 (1.24)	4.49 (1.26)	0.30
Critical Thinking	3.91 (1.28)	3.70 (1.22)	0.62
Metacognition	4.88 (0.58)	4.47 (0.67)	0.09
Time and study environment	5.68 (0.69)	5.15 (0.79)	0.04
Effort regulation	5.88 (0.77)	5.48 (0.91)	0.15
Peer learning	4.66 (1.45)	3.56 (1.38)	0.03
Help seeking	5.05 (1.15)	4.15 (1.32)	0.03

TABLE 2. Baseline differences on motivational and learning strategies. A 7-point Likert scale was used with 1 indicating "strongly disagree" and 7 indicating "strongly agree". $\alpha = 0.05$.

We also examined possible differences between learning practices and attitudes about science between groups. We observed no difference in the learning practices and attitudes about science between the two groups (Table 3).

Item	**Participants who took Invasion of the Grackles (SD)**	**Participants who took Cracking the Next Pandemic (SD)**	**P value**

Real World Connection	23.9 (3.51)	23.32 (2.83)	0.57
Problem Solving Difficulty	18.6 (3.36)	18.05 (4.09)	0.652
Enjoyment	22.4 (5.33)	23.32 (3.92)	0.543
Problem Solving Effort	25.5 (4.15)	25.11 (2.90)	0.732
Conceptualization / Memorization	20.05 (3.33)	18.68 (2.26)	0.142
Problem Solving Strategies	15.5 (2.46)	14.94 (2.04)	0.449
Reasoning	20.3 (2.94)	19.53 (2.97)	0.419

TABLE 3. Baseline differences between learning practices and attitudes about science. A 5-point Likert scale from "strongly disagree" to "strongly agree" was used. $\alpha = 0.05$.

Individuals who took *Invasion of the Grackles* completed more actions.

We observed statistically significant differences among the average number of information seeking actions, average number of tests, and average amount of total action, between individuals who took *Invasion of the Grackles* and individuals who took *Cracking the Next Pandemic*. Those who took *Cracking the Next Pandemic* were more likely to complete more information seeking actions and perform more tests. (Table 4).

Type of Action	Average Number of Information Seeking Actions (SD)	Average Number of Hypothesis (SD)	Average Number of Tests (SD)	Average Total Number of Actions
Individuals who took Grackles	**1.26 (2.05)**	1.37 (0.56)	**3.89 (2.64)**	**6.63 (4.19)**
Individuals who took Pandemic	**6.10 (4.86)**	1.37 (0.56)	**5.63 (1.8)**	**15.2 (5.78)**

TABLE 4. Actions performed by the two populations. Data are presented as mean values with the standard deviations (SD) in parentheses. The average number of hypothesis and the average number of tests are a subset of investigative actions.

Individuals who took *Cracking the Next Pandemic* completed more complex investigations.

Prior work by Peffer and colleagues (2020) suggests that undergraduates with more sophisticated EBAS are more likely to complete complex investigations with some kind of systematic focus when examining a problem. Investigative style and general patterns of actions performed during SCI were assessed to examine differences between the two simulations.

Investigation type was separated into two categories: simple and complex. I examined investigative profiles of 10 candidate participants who completed *Invasion of the Grackles* (Figure 1). I noted often times individuals who completed a complex investigation would look for information before making a hypothesis. Next, I looked at the investigative profile of participants who completed *Cracking the Next Pandemic* (Figure 2). Again, I found a similar pattern that many complex investigations included searching for information before making a hypothesis. Finally, we compared the type of investigation completed by individuals who completed *Invasion of the Grackles* and *Cracking the Next Pandemic* (Figure 3). We noted that participants who completed *Cracking the Next Pandemic* simulation were more likely to complete a complex investigation (Figure 3).

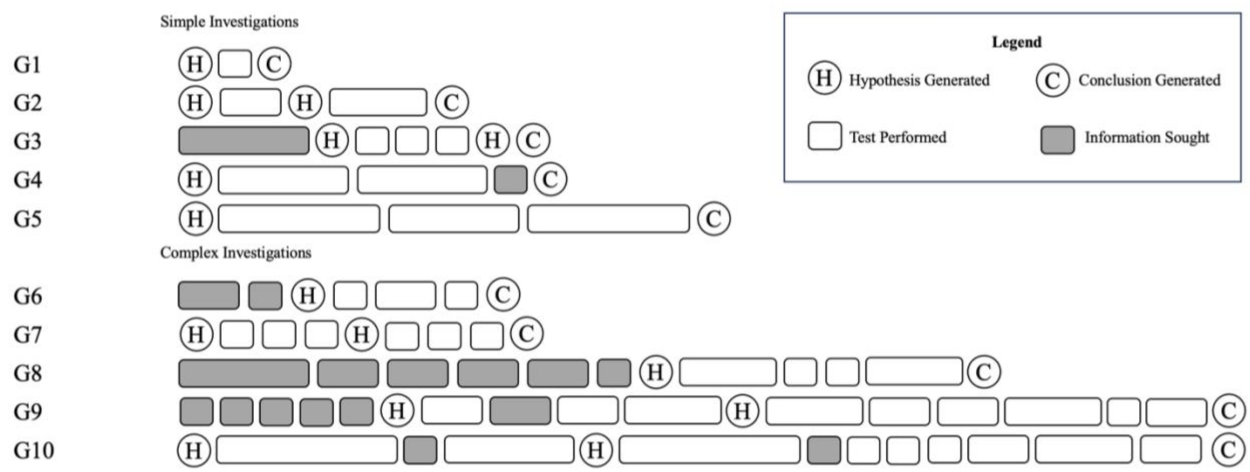

Figure 1. Examples of investigations completed by Invasion of the Grackles Participants.

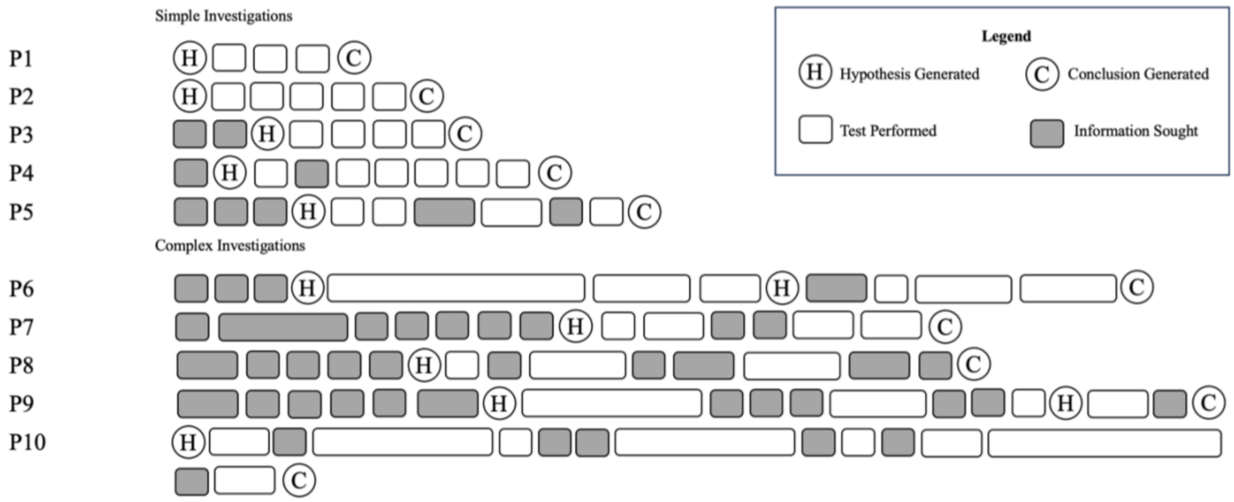

Figure 2. Examples of investigations completed by Cracking the Next Pandemic Participants.

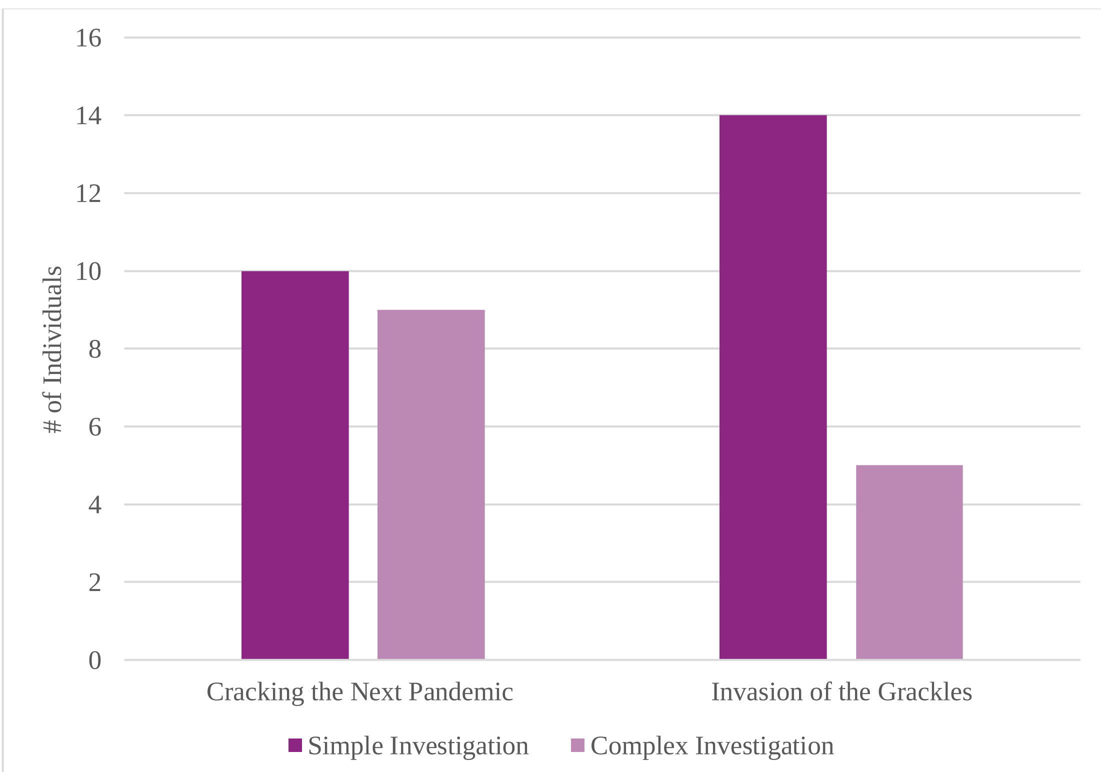

Figure 3. Differences in complexity of investigation between populations.

	Average Number of Investigative Actions (SD)	Average Number of Hypothesis (SD)	Average Number of Tests (SD)	Average Total Number of Actions
Invasion of the Grackles, Current Study	4.0 (2.65)	1.37 (0.56)	3.89 (2.64)	6.63 (4.19)
Cracking the Next Pandemic, Current Study	7.74 (2.23)	1.37 (0.56)	5.63 (1.8)	15.2 (5.78)
Invasion of the Grackles, undergraduates (2020)	2.25 (3.69)	1.30 (0.59)	4.26 (2.44)	8.98 (4.09)
Invasion of the Grackles, graduate students (2020)	5.71 (11.20)	1.36 (0.63)	6.14 (2.74)	14.21 (12.28)

TABLE 5. Actions performed by the two populations compared to past data.

Number of actions by *Cracking the Next Pandemic* participants are similar to the number of actions by graduate students.

Since test subjects have changed since the pandemic and the widespread disruption of in-person education (Peimani & Kamalipour, 2021), we wanted to determine if there was any reason to expect changes to our model as the result of changing students in a post-COVID-19 pandemic world. The data from this investigation was compared to data collected in 2020 prior to the COVID-19 pandemic among undergraduate biology students and graduate biology students (who served as a comparison group that had sophisticated epistemological beliefs) who completed *Invasion of the Grackles*. The data from *Invasion of the Grackles* among biology undergraduate students by Peffer and colleagues in 2020 is comparable to biology undergraduates' students who took *Invasion of the Grackles* in this study. However, we noted that undergraduate students in the current study who completed the *Cracking the Next Pandemic* were comparable to graduate biology students who completed the *Invasion of the Grackles* as part of a previous study (Peffer et al., 2020). For example, the average number of tests that graduate students completed in *Invasion of the Grackles* was similar to the average number of tests that undergraduate students completed in *Cracking the Next Pandemic*.

Discussion

The demand for STEM employees has already outpaced the number of college graduates with a STEM degree (Lucas and Spina, 2022). However, a possible and promising route to combatting this problem is to improve science education (Sithole et al., 2017). One possible way of improving science education is by attending to EBAS in the classroom. Since EBAS influences how students learn in a science classroom (Peffer and Ramazani, 2019), it is important to understand how EBAS are conceptualized within biology and between biology subdisciplines. This will open the door to future studies on best practices for incorporating EBAS instruction into classrooms. Examining EBAS among subdisciplines of biology could give even more insight into how individuals form sophisticated epistemological beliefs in different biology classes, ultimately providing better guidance on how to teach about the process of science in various biology classrooms.

Difference in inquiry practices between the two simulations.

We noted that there was a difference in inquiry practices between the two simulations. These differences were not the result of baseline differences in motivation or learning strategies as assessed using the MSLQ and CLASS-Bio. Those who took *Cracking the Next Pandemic* were more likely to complete more information seeking actions, perform more tests, and overall complete a more complex investigation than students who completed the *Invasion of the Grackles* simulation.

Since *Invasion of the Grackles* was designed based on a field-based ecological study, while *Cracking the Next Pandemic* was designed to be a lab-based molecular biology study, it may be that the subdomain of the simulation could influence the types of practices that we are seeing. This begs the question of if the simulation content from various subdomains is resulting in different inquiry practices unrelated to differences in EBAS. From my data, the subjects' number of testing actions or investigative actions did not seem to have a significant bearing on determining the sophistication of that subject's EBAS. Rather, the way they created hypotheses, came to conclusions, and rationalized their approach to the simulation seemed to be a better indication. For example, while one subject may have completed every test available to them, they may have only generated a single hypothesis and may have picked tests randomly, instead of having some type of systematic approach. Participants completing the *Cracking the Next Pandemic* simulation showed more nuanced and thoughtful approaches to the simulation. Therefore, it could also be possible that the different contexts could be causing students to engage in a more sophisticated manner. A possible future experiment could be to look at students who perform the *Cracking the Next Pandemic* simulation followed by *Invasion of the Grackles* and view if taking the *Pandemic* simulation first influences practices in *Grackles.* Another possible future experiment could be evaluating the question, how do students respond differently if their major matches the content at hand?

Practices by *Cracking the Next Pandemic* participants are reminiscent of expert like practices used by graduate students.

Due to the shifts in test subjects brought on by the pandemic and the extensive upheaval in traditional education, I wanted to see whether adjustments to our model were warranted. I compared our results to previous data collected in 2020 prior to the COVID-19 pandemic (Peffer et al., 2020). We noted that although the studies used students from different universities (although both public universities in the same state), the two populations had similar SCI simulation practices. This suggests that, at least using our model system, the COVID-19 pandemic did not influence student's EBAS as seen through SCI simulation practices in *Invasion of the Grackles*. After observing that individuals who took *Cracking the Next Pandemic* completed more complex investigations, I wanted to compare these investigations to past investigations completed by individuals with more experience participating in authentic science inquiry and more sophisticated epistemological beliefs about science, namely biology graduate students. I found that undergraduate students who took *Cracking the Next Pandemic* had practices more reminiscent of the biology graduate students who completed *Invasion of the Grackles* (Peffer et al., 2020). We hypothesize that these similarities could be due to the simulation content area. For example, different content areas could be impacting how students conceive of and perform their investigations.

Limitations and future directions.

One of the major limitations of our study currently is the sample size. With a mere 38 subjects, we cannot say for certain that our data is indicative of the entire undergraduate biology population. Our subject pool was also mostly white and limited to students at a prestigious RO1 university. However, similar practices between the undergraduates who took *Invasion of the* Grackles in 2020 and undergraduates who took *Invasion of the Grackles* in 2022 indicate internal reliability. Also, among these subjects, we only recruited from individuals who were in an introductory to molecular biology course.

In future work, I will look at other factors that could explain the differences in practices between the two simulations. For example, does the language used and presentation of the problem in each simulation influence how a subject interacts with the simulation? We will also examine other factors that could influence our interpretation of EBAS, including nature of science understanding and science identity. Nature of science is a construct that is closely related to EBAS and could influence EBAS as seen through practices (Peffer et al., 2020). We will also use think-aloud protocols as participants complete the simulation and interviews that will take place directly after a subject completes the simulation to qualitatively assess students' EBAS and interrogate how these beliefs may have influenced their inquiry practices. For example, are participants who take *Cracking the Next Pandemic* completing all the tests because they are confused? We also plan to conduct research to determine if the simulations themselves are influencing how a subject interacts with the simulation. To do this, we plan on experimenting with separate versions of the *Invasion of the Grackles* simulation to ensure that it is in fact equal in content to *Cracking the Next Pandemic*.

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