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Agar Art: a CURE for the Microbiology Laboratory

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We previously developed and assessed "The Art of Microbiology," a course-based undergraduate research experience (CURE) which uses agar art to spur student experimentation, where we found student outcomes related to science persistence. However, these outcomes were not correlated with specific activities and gains were not reported from more than one class. In this study, we explored which of the three major activities in this CURE—agar art, experimental design, or poster presentations—affected student engagement and outcomes associated with improved understanding of the nature of science (NOS). The Art of Microbiology was studied in three microbiology teaching laboratories: at a research university with either the CURE developer (18 students) or a CURE implementer (39 students) and at a community college with a CURE implementer (25 students). Our quasi-experimental mixed methods study used pre/post-NOS surveys and semi-structured class-wide interviews. Community college students had lower baseline NOS responses but had gains in NOS similar to research university students post-CURE. We surveyed research university students following each major activity using the Assessing Student Perspective of Engagement in Class Tool (ASPECT) survey but did not find a correlation between NOS and activity engagement. Of the three activities, we found the highest engagement with agar art, especially in the CURE developer class. Interviewed students in all classes described agar art as a fun, relevant, and low-stakes assignment. This work contributes to the evidence supporting agar art as a curricular tool, especially in ways that can add research to classrooms in and beyond the research university.

KEYWORDS course-based undergraduate research experience, interdisciplinary, agar art, science education, microbiology laboratory, community college, undergraduate

INTRODUCTION

> Neither science nor the arts can be complete without combining their separate strengths. Science needs the intuition and metaphorical power of the arts, and the arts need the fresh blood of science.
>
> —E. O. Wilson

In "Consilience: The Unity of Knowledge" (1), E. O. Wilson posits that art and science need to achieve consilience, or a coming together, in order to further human knowledge. However, many college science classrooms are far from that ideal, and creativity and interdisciplinarity are rare in science teaching laboratories. Most laboratory classes use cookbook models where students follow linear preprepared experimental protocols without having to make experimental choices (2). The curricular choice to not require students to develop or execute scientific choices may ill equip students for professions in science and reduce the likelihood that they will ultimately join the science, technology, engineering, and mathematics (STEM) workforce (3). On the other hand, students whose laboratory courses include authentic science experiences in course-based undergraduate research experiences (CUREs) show increased self-identification as scientists as well as increased persistence in the sciences (4). CURE curricula teach students to effectively use current scientific tools, troubleshoot procedures, replicate their findings, and create novel data potentially of interest to outside stakeholders or researchers (2, 5). While all CUREs engage students with authentic research, most do not have students generate their own personalized research questions, instead relying on pre-existing frameworks associated with faculty research programs which are rarely available to students who are not at 4-year research-oriented institutions.

Inspired by Wilson's concept of consilience (1), we found ourselves considering ways to include personal experimental

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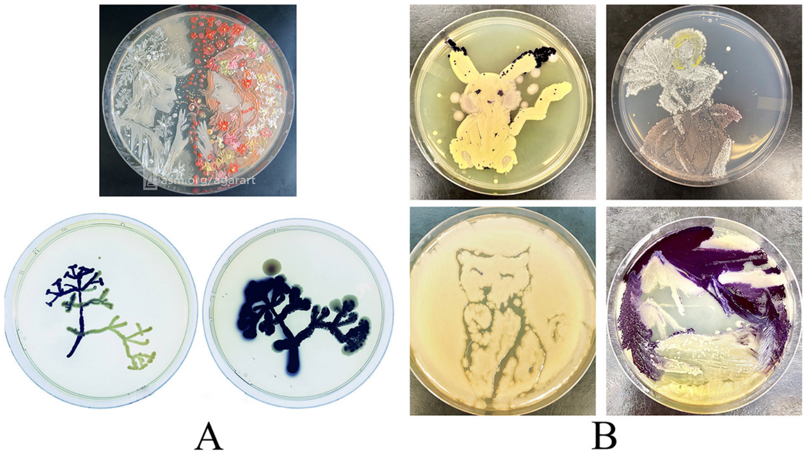

FIG 1. Agar Art Examples. (A) Entries to the American Society for Microbiology 2018 agar art contest. (Top) "The battle of winter and spring," by Ana Tsitsishvili, 2018 ASM Agar Art 1st place winner. Pigmented strains producing antibiotics depigment nearby strains. Used with written permission. (Bottom) "I think," by Sarah Adkins-Jablonsky, a 2018 ASM Agar Art finalist. The two trees of life represent early and late stages of the painting made using *Chromobacterium violaceum*. (B) Four student agar artwork examples. Bacteria were isolated from the soil and used to trace over paper template designs onto BHI or R2A agar using sterile toothpicks, cotton swabs, or inoculating needles. These representative works were produced by UAB students enrolled using The Art of Microbiology curriculum in Spring 2020 (used with verbal permission).

design in a portable and inclusive CURE around the same time that agar art, or painting using pigmented bacteria, was rising in popularity online and elsewhere. For example, each year since 2015, the American Society for Microbiology has solicited agar art paintings for their highly publicized annual contest (Fig. 1A), and agar art appeared on a recent cover of Humanism Evolving through Arts and Literature (HEAL), a journal directed toward health care professionals (6). For the public, seeing the tangible outputs of bacterial gene expression in the form of fluorescent and chromogenic pigments promotes a unique perspective for approaching microbiology, but the appreciation of agar art has a long history: the first recorded agar artist was actually the famous microbiologist Sir Alexander Fleming (7). Fleming was teaching himself how to paint with watercolor and eventually brought this hobby into the laboratory, creating portraits of mothers, wrestlers, and others using bacteria in petri dishes. This creative dabbling may have led him toward his experiments with what he then called "slime mold" (7), but would later be called *Penicillium* ("paintbrush") and would lead to a discovery that would change the course of history.

Because of its popularity, we began to wonder if agar art could be useful not just in the public sphere, but also in the microbiology classroom. One study found that simply viewing an agar art exhibition increased visitors' understanding of fundamental microbiology concepts (8), and so perhaps agar art could have a similar effect on students. Many stakeholders have commented on the need for interdisciplinarity in the science classroom (9–12), and in particular, the pedagogical benefits of integrating art into existing science curriculums as science, technology, engineering, arts, and math (STEAM) have attracted attention since the idea was born at a U.S. National Science Foundation workshop in 2011 (13). However, while there have been calls for the incorporation of agar art specifically (14, 15) as well as related creative arts (16) in science education and outreach, there has been little research on agar art's effectiveness as a curricular tool.

We saw agar art as an opportunity for CURE students to explore the peculiar ecophysiologies of pigmented microbes, as their interactions inevitably affect the outcome of planned artworks (Fig. 1B). Reasoning that these observations could stimulate novel experimentation outside the context of faculty-driven research programs, we decided to build an entire curriculum around this concept and developed The Art of Microbiology (17), a 16-week semester-long introductory microbiology laboratory course using agar art. We demonstrated in an earlier study that students who participated in this curriculum self-reported higher measures of scientific identity than a similar cohort using the previous cookbook laboratory curriculum (18). These results were promising, but because the agar art was integrated as one element in a broader CURE context, these data alone did not demonstrate whether the agar art or the other CURE components were responsible for the measured improvements. Additionally, our former work only explored outcomes related to persistence in the sciences (4), but we were also interested to know if students experienced improvements in course engagement (19, 20), scientific thinking (20, 21), experimental design competence (20, 22), and overall academic performance (19, 20). Collectively, these learning goals encompass the nature of science (NOS) and represent one of the most enduring and important goals in science education. Incorporation of NOS as a way of thinking is equated with science epistemology, i.e., the embrace of science and scientific methodology as a system for constructing knowledge (23, 24). In this work, we addressed these knowledge gaps by comparing outcomes for three different student cohorts who used The Art of Microbiology, including two courses at a research-intensive public university and one at a nearby community college.

TEXT BOX 1. Description of the three central student activities from The Art of Microbiology.

Agar art

Agar art is a form of biological art where colonies of pigmented microbes are painted or drawn onto agar medium using sterilized applicators. To make replicable drawings, students drew any picture they desired on a circular paper template the size of a petri dish and taped their sketch under their agar plate "canvases." Because the agar medium is mostly transparent, students were able to trace over the sketch onto the agar. Each student made three near-exact replicates of their agar art, either using different medium formulations (e.g., R2A or brain heart infusion [BHI] broth) incubated at the same temperature or using the same medium but incubated at three different temperatures. Each student used their teams' two soil bacterial isolates in addition to other bacterial cultures from the other student teams (or provided by the laboratory coordinator) to create their art.

Designing experiments

Beginning shortly after completing the agar art assignment and continuing for several weeks, student teams worked to formulate hypotheses involving their isolates and to design experiments to test them. As raw material for these brainstorming sessions, the students used results from their experiments (e.g., growth on differential media indicating physiological capabilities, microscopic observations and Gram stain results, and environmental tolerance ranges) as well as unexpected observations from their agar art plates. They were required to suggest multiple hypothesis statements and, over several class periods, worked with their laboratory instructor to decide on one hypothesis that was testable, reasonable, and appropriate for the timing and resources of the CURE course. Once they solidified their statement, they consulted with the instructor to make a list of materials and resources they needed to carry out their experiments and then spent the remainder of the semester executing and, if necessary, troubleshooting these experiments. Examples of hypotheses tested by students are listed below:

- *Hymenobacter gelipurpurascens* pigment changed from red to yellow because of lower pH levels.
- The production of fibrous projections in our isolate is a reaction to environmental stresses, including UV radiation.
- Production of spores in our isolate is a temperature-dependent process.
- *Pseudomonas oryzihabitans* is capable of antibiotic production.

Poster presentations

On the second-to-last day of class, student teams created hand-drawn or printable posters to share their team's experimental design and results. In the final laboratory class, student teams presented their results to the rest of their laboratory section during a poster session similar to what one might find at a professional conference or research expo.

Our research questions are as follows:

1. How do nature of science attitudes vary across student cohorts at a research university and a community college?
2. Is there a relationship between nature of science attitudes and engagement with either agar art, designing experiments, or poster presentations?
3. Are students indicating higher engagement with agar art than with designing experiments or poster presentations?

We expected baseline NOS attitudes would vary across our student cohorts. We then predicted that engagement as indicated by Assessing Student Perspective of Engagement in Class Tool (ASPECT) responses would be related to a particular student's NOS gains. In other words, we expected students that engaged more with the curriculum would experience the greatest NOS improvements. Lastly, we hypothesized that students would have higher engagement with agar art than experimental design and poster presentations, especially as indicated by ASPECT-6, "I had fun during today's ______ activity."

(Portions of this curriculum or work have been presented at the Society for the Advancement of Biology Education Research [SABER] in 2019 and 2020, Gordon Research Conference [GRC] and Seminar in Undergraduate Biology Education Research [UBER] in 2019, ASMCUE in 2018, and ASM Microbe in 2018.)

TEXT BOX 2. NOS and ASPECT questions.

Nature of science (NOS) questions (scored on a 5-point Likert scale from strongly disagree [1] to strongly agree [5]):

1. The study of biology is only useful when it directly benefits human health or wellbeing.
2. The more hypotheses an experiment attempts to test, the better.
3. If I had the necessary materials, I could conduct a successful biology experiment.
4. I am confident that I can design a valid biology experiment.
5. I think about the biology I experience in everyday life.
6. Biologists may make different interpretations on the same observations.
7. Biologists do NOT use their imagination because it can interfere with scientific reasoning.
8. Experiments that are done under laboratory conditions can provide information that applies to the real world.

ASPECT survey questions (blanks were filled in with the appropriate activity from Text Box 1 for each interval survey):

1. Explaining the material to my group improved my understanding of it.
2. The instructor's enthusiasm made me more interested in the ______ activity.
3. Having the material explained to me by my group members improved my understanding of the material.
4. Group discussion during the _____ contributed to my understanding of the course material.
5. The instructor(s) put a good deal of effort into my learning for today's class.
6. I had fun during today's ______activity.
7. Overall, the other members of my group made valuable contributions during the ______ activity.
8. The instructor seemed prepared for the _______ activity.
9. I would prefer to take a class that includes this ________ group activity over one that does not include this _______ group activity.
10. I am confident in my understanding of the material presented during today's _______ activity.
11. I made a valuable contribution to my group today.
12. The instructor and TAs were available to answer questions during the _______ activity.
13. The ______ activity increased my understanding of the course material.
14. I was focused during today's ______activity.
15. The _______ activity stimulated my interest in the course material.
16. I worked hard during today's _______activity.

METHODS

All laboratory courses in this study used The Art of Microbiology, a 16-week CURE curriculum (see Fig. S1 in the supplemental material). Students isolated soil bacteria and used biochemical tests and 16S rRNA gene sequencing to identify and characterize their isolates. Midway through the semester, they created agar art (Fig. 1B), and in the second half of the semester, they created hypotheses based on their artwork and identification results and carried out student-designed experiments to test those hypotheses (see Fig. S1). Finally, students presented the results of their experiments in professional-style manuscripts and with a poster presentation. More details, including student learning objectives, research objectives, and safety precautions (such as adherence to ASM guidelines for biosafety in teaching laboratories), can be found in the CUREnet repository (25) (https://serc.carleton.edu/curenet/collection/216123.html). This involves working at biosafety level 2 (BSL2) and special precautions, preliminary training, and oversight by University biosafety professionals is necessary. The open-access curriculum, including both the most recent version and the previous versions used for the courses described here, is available at https://figshare.com/articles/The_Art_of_Microbiology_A_Laboratory_Manual/5487214.

Three different implementations of The Art of Microbiology were assessed in three separate semesters, each taught by a different instructor. The first two courses, designated UAB1 and UAB2, were taught at the University of Alabama at Birmingham, a 4-year research-oriented university, whereas the third course, designated JSCC, was taught at Jefferson State Community College, one of the largest community colleges in the state of Alabama. The UAB1 instructor was one of the original developers of The Art of Microbiology, while the UAB2 and JSCC instructors were not and are therefore referred to as "implementers." We find this distinction important considering Shortlidge et al. (26) found that CURE developer and implementer experiences and motivations varied greatly. More detail about UAB1, UAB2, and JSCC instructor experience and motivations can be found in Appendix S1 in the supplemental material under "Course Descriptions."

This study was approved by the UAB IRB 300000152. In total, we had 18 complete responses from UAB1, 39 students' complete responses from UAB2, and 25 complete responses from JSCC. More information about administration and participation rates can be found in Appendix S1 in the supplemental material under "Administration and Participation."

We used a mixed-methods approach with a combination of survey instruments (Text Box 2) and class-wide interviews to assess the impact of the three major course components described in Text Box 1. At the beginning and end of each semester, we used eight survey items developed in an attitudinal survey that assessed students' understanding of NOS. The two main groupings of statements are (i) "confidence and interest in scientific inquiry" and (ii) "understanding and acceptance of scientific inquiry" and are scored on a 5-point Likert scale from strongly disagree (1) to strongly agree (5) (20). For UAB1 and UAB2, we also administered interval surveys derived from the assessing student perspective of engagement in class tool (ASPECT) (27). The assessing student perspective of engagement in class tool (ASPECT) is a 16-item survey that is one of the only surveys to assess student engagement with specific active-learning practices. Statements are scored on a 6-point Likert scale from strongly disagree to strongly agree and can be categorized in the following groupings: (i) value of activity, (ii) personal effort, and (iii) instructor contribution (27). Alongside each interval survey, we also conducted 10-min recorded semi-structured interviews with students asking about their positive and negative experiences in the class using questions from the UT Arlington student feedback survey for laboratory sections (see Appendix S2 in the supplemental material). Interval surveys and interviews at UAB1 and UAB2 were administered immediately after the three focal activities described in Text Box 1. Interviews were also performed at JSCC, but only once, at the end of the semester immediately before the final exam. Indeed, we note that concerns related to class time meant that JSCC students did not have interval surveys or interviews. Statistical differences between semesters and between pre- and postsurvey were assessed using linear mixed-effects models in R (see Appendix S1 for more detail under "Quantitative Methods"). Interviews were transcribed and statements were open coded independently (28) by two researchers without considering the specific research questions of this study. After initial codes were developed, the coders came to a complete consensus about the coding framework and used it to develop the themes and subthemes reported here (see Appendix S1 for more detail under "Qualitative Methods").

See Table 1 for an overview of assessments and study design from the present study alongside earlier studies at UAB using either The Art of Microbiology (UAB0) or the previous cookbook style lab (UAB00) (18).

RESULTS

How do nature of science attitudes vary across student cohorts at a research university and a community college?

There were significant differences in presemester baseline attitudes between students at the community college (JSCC, 18 students) and students at the 4-year institution (UAB1, 39 students; UAB2, 25 students) (Fig. 2A). Students in JSCC were more likely to agree with statements NOS-1, NOS-2, and NOS-7, and they were less likely to agree with statement NOS-5 (see Text Box 2 for statement text). Three of these statements (NOS-1, NOS-2, and NOS-7) were the opposite of expert-like attitudes, and so higher agreement by JSCC students represented more dissonance between student and expert attitudes. There were no statistical differences in presemester NOS attitudes between UAB1 and UAB2. Also, while there were some demographic differences between JSCC and UAB1/UAB2 (e.g., the majority of JSCC students who reported demographic information were first-generation college students and self-reported qualifying for income-based finical aid) (see Table S1 in the supplemental material for complete demographic information), we did not find that any of the demographic variables we assessed (gender, race/ethnicity, grade point average [GPA], English as a second-language [ESL] status, free application for federal student aid [FAFSA] status, or first-generation status) significantly predicted any survey responses.

Despite these baseline differences, the effects of the course on both JSCC and the UAB1/UAB2 cohorts were statistically indistinguishable. We identified significant changes pre- to post-semester in attitudes toward several of our NOS survey instruments (Fig. 2B). Students in all three courses experienced similar gains in agreement to the statements NOS-3, NOS-4, and NOS-5, supporting our prediction that participation in the CURE would have a positive effect on student appreciation of NOS.

Are students indicating higher engagement with agar art than with designing experiments or poster presentations and is there a relationship between nature of science attitudes and engagement with either agar art, designing experiments, or poster presentations?

We also surveyed students in UAB1 and UAB2 at three intervals throughout the semester immediately following the class periods where the major active-learning components of the course took place: making agar art, designing an experiment, and creating posters (see Text Box 1 for further descriptions of these activities). We found that students had the highest engagement with agar art and the lowest engagement with experimental design. Both agar art and poster presentations outperformed experimental design on statements related to value and instructor contribution (ASP-6, ASP-8, ASP-9, ASP-10, and ASP-15) (see Text Box 2 for statement descriptions). For the poster presentation compared to the experimental design exercise, students further reported the instructor was more enthusiastic (ASP-2), group discussions were more productive (ASP-4), and the activity itself was more academically effective (ASP-13). There were also clear differences in average Likert scores for the ASPECT questions between time points and between the two courses. For both UAB1 and UAB2, time point 2 (after experimental design) average scores were significantly lower than either time point 1 or 3 (after agar art or poster presentations, respectively) (Fig. 3).

TABLE 1
Overview of assessments on Art of Microbiology curriculum

Category	Semester[a]				
	Fall 2016	Spring 2017	Fall 2017	Spring 2018	Fall 2019
Curriculum	*Traditional*	*Agar art CURE*	Agar art CURE	Agar art CURE	Agar art CURE
Class code/student cohort	*UAB00/R1 200-level (n = 33)*	*UAB0/R1 200-level (n = 15)*	UAB1/R1 200-level (*n* = 18)	UAB2/R1 200-level (*n* = 39)	JSCC/CC 200-level (*n* = 25)
Survey format	*Paper*	*Paper*	Paper	Paper	Paper
Pre/ postassessments	*PITS (post only)*	*PITS (post only)*	NOS	NOS	NOS
Interval assessments	*None*	*None*	ASPECT	ASPECT	None
Interviews	*Offered, no participants*	*Post*	3 intervals	3 intervals	Post

[a]Italic font represents previously published research (18). Agar art CURE, use of Art of Microbiology curriculum; UAB00 and UAB0, previous iterations of microbiology taught at UAB; R1, research-intensive university; CC, community college; PITS, persistence in the sciences.

UAB1 scores were also significantly higher than UAB2 scores at both time points 1 and 2. We had also predicted that students who had higher engagement with agar art, as indicated by the ASPECT survey, would be more likely to have expert-like NOS attitudes. However, no ASPECT response was a significant predictor of NOS responses.

In addition to using survey instruments, we interviewed student participants. UAB1 and UAB2 students were interviewed following their participation in each of three curricular events (Text Box 1), whereas JSCC students were interviewed only once, at the end of their semester due to time constraints. Table 2 reflects themes present in these interviews, and Text Box 3 provides representative quotes corresponding to the themes (see Table S2 for additional themes not discussed here). The three focal curriculum topics are listed first, with subsequent themes in the order in which they appeared in the transcriptions. Some themes were apparent in conversations before, during, or after the interview related to that theme. For example, UAB1

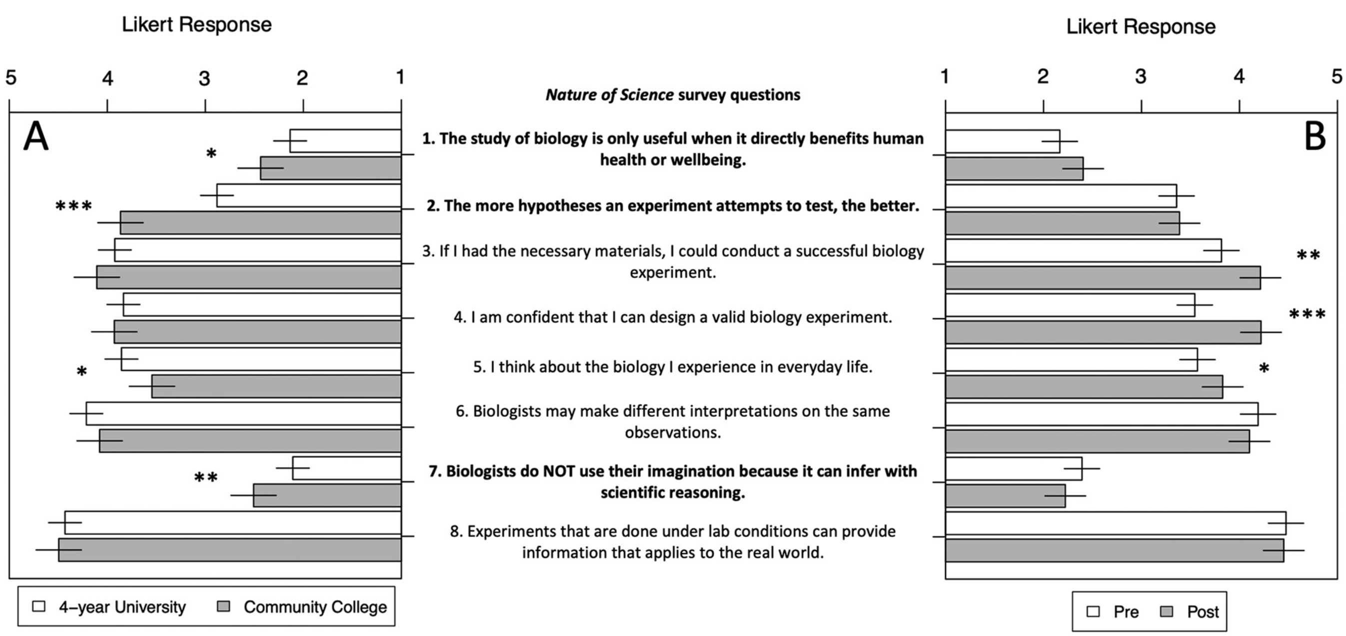

FIG 2. Likert responses to NOS survey questions. (A) Baseline differences from presemester surveys in NOS responses in two combined 4-year university classes (UAB1 and UAB2) compared with a community college (JSCC) class using The Art of Microbiology. (B) Changes (pre to post) in responses of all students enrolled in the study. Likert statements followed a 5-point scale, where 1 was strongly disagree, 3 was uncertain, and 5 was strongly agree. Bolded statements (NOS-1, −2, and −7) are "reverse" statements, where lower Likert responses would be expected from expert respondents. Error bars indicate 95% confidence intervals of the means estimated from a linear mixed-effects model, and asterisks indicate significance levels from *post hoc* pairwise comparisons. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

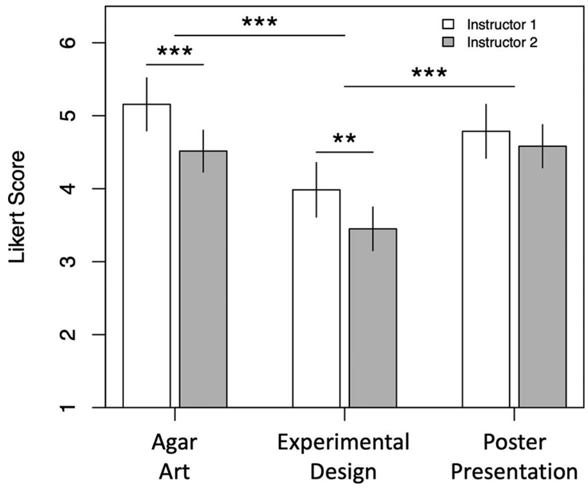

FIG 3. Student engagement with active-learning strategies as measured by the ASPECT survey. UAB1 (instructor 1) and UAB2 (instructor 2) students' average ASPECT responses at time points 1, 2, and 3 showed clear differences between time points as well as between student cohorts. Likert scale ranges from strongly disagree (1) to strongly agree (6), with no value indicating uncertainty. Error bars indicate 95% confidence intervals of the estimated group means from a linear mixed-effects model, and asterisks indicate significance levels from *post hoc* pairwise comparisons. **, $P < 0.01$; ***, $P < 0.001$.

and UAB2 students talked about agar art being a fun creative outlet during their interview following agar art (1st interview) but also following the poster presentations (3rd interview). As another example, UAB1 students recognized they were making their own research choices (during 1st interview) even before designing an experiment (2nd interview).

While interviews helped us find trends between universities, we did not have scripted questions about the focal topics in Text Box 1 or other questions related to our hypothesis. We reasoned that not asking students about these topics specifically would help eliminate the chance students would only say what they thought we wanted to hear (also known as demand characteristics) (29), but it also created the possibility that students would not share their opinions about the key elements we sought to study. For example, anecdotal evidence and student reviews for E. Arnold showed that JSCC students greatly enjoyed giving their poster presentations, especially inviting their friends and family to watch them present (data not shown). However, JSCC students did not specifically mention poster presentations in their interviews (Table 2). In other words, the absence of a theme from an interview does not indicate that theme did not resonate with students but simply that they did not mention it during their interviews.

DISCUSSION

The Art of Microbiology produced similar shifts in attitude for both 4-year university and community college students

The three classes under consideration here provide a sample of the diversity of approaches to introductory microbiology, ranging from practical medical science microbiology to academic microbiology *sensu lato* (30, 31), and therefore allow us to consider whether laboratory pedagogies and CUREs can reach across these content divides. First, we investigated how baseline NOS attitudes varied across our student cohorts. Most notably, we found that JSCC students were significantly less likely to express expert attitudes on statements about human health, hypothesis testing, and scientific imagination than our university students (Fig. 2A). We did not detect baseline differences between UAB1 and UAB2. Our results contrast with work by Beumer (32) who showed that 2-year college students had baseline science attitudes similar to students at other institutions. However, we believe these baseline differences are less important than the fact that we observed gains in NOS attitudes across all three cohorts, and the magnitudes of these gains were not significantly different between 4-year and community college classes (Fig. 2B). The NOS-3 and NOS-4 items in particular (Text Box 2) assessed our direct backwards-design goals (33) for creating The Art of Microbiology curriculum.

Next, we compared qualitative results across all courses to ascertain whether or not students had similar experiences and outcomes. Students at JSCC brought up one especially important theme that UAB students did not mention: having a sense of personal investment in making their own experimental choices (Table 2). Thus, more community college instructors could implement CUREs like The Art of Microbiology that involve students making their own experimental choices. It could be that JSCC students may have had different expectations about their research experiences given the dearth of authentic research opportunities in their community college (34). Regardless, expressions of project ownership reflect one of the key predictors of persistence in science majors (4) and could be worth continued exploration. There were also several themes present in the UAB1 and UAB2 classes that were absent from the JSCC class, including both positive (enjoying the interactivity and/or connectivity of the lab curricula) and negative comments (feeling rushed, having trouble with statistics) (Table 2). Whether or not UAB1, UAB2, and JSCC students may have had different expectations for their laboratory experiences based on their previous educational experiences and participation in research experiences, we still see that, collectively, these students experienced similar improvements in their attitudes toward NOS.

These results and those in our previous report (18) indicate that a CURE centered around agar art, where students design their own experiments based partially on observations of their agar art plates, can improve student confidence and perceived ability to design experiments, in other words, their sense of self-efficacy as a scientist. Because The Art of Microbiology was the only common element in all three of these courses, we suspect that the CURE played a role in students' changed attitudes about the practice of science. Other studies have shown similar effects from guided-inquiry laboratories specifically in community college settings (35), but to our knowledge, our study is the

TABLE 2
Themes from interviews during three separate semesters (condensed)[a]

Theme	Subtheme	Interviews[b]		
		UAB1	UAB2	JSCC
Agar art (1)	Fit well in curriculum or was low stakes	1, 3	1, 2 (b)	Post
	Was cool, fun, or creative visualized outlet	1 (a), 3	1 (c), 3	Post (e)
	May have enjoyed but did not clearly help or fit well into curriculum	1, 3	1, 3 (d)	
Making own choices/ designing experiments (2)	Enjoyable, able to apply knowledge	1, 2, 3		Post
	Felt unprepared, intimidated	2	2	
	Personal investment			Post (g)
Poster presentations (3)	Enjoyable to make and seeing what other experiments were on	3 (h)	3 (i)	
Research	Enjoyable yet unpredictable		1	Post
	Applied, generated knowledge	1	1	
	Interactive/hands on	1	1, 2	
Visualizing changes	Liked visualizing biochemical tests			Post
Personal	Liked lecture professor regularly visited lab	1, 2		
	Liked their teacher, including teaching demos	1, 2, 3	2, 3	Post
	Felt listened to by education researcher team	2	3	
	Valued student lab teams/groups	1	1	
Lab experiments	Felt rushed/fast paced	2, 3	1, 2, 3	
Statistics	Warranted more instructional time or prerequisite in statistics	3	2, 3	
Future goals	CURE not applicable to specific future goals (i.e., practicing medicine)	2, 3		
	CURE applicable to future goals (e.g., can put on CV)		2	

[a]UAB interviews were at three different intervals throughout their respective semester: after agar art (1), after designing their own experiments (2), and after poster presentations (3). Italicized themes and themes not discussed in the main text are provided in Table S2 in the supplemental material.
[b]JSCC interviews occurred just once, at the end of the semester, as indicated by "Post." Lowercase letters in parentheses refer to representative student quotes in Text Box 3.

first to show the portability and effectiveness of an art-infused CURE curriculum across both community college and 4-year university contexts.

Agar art has high engagement value in The Art of Microbiology

Experimental design and poster presentations are common personalized components of CUREs (5, 36, 37), but the use of agar art in a CURE is a novel aspect of The Art of Microbiology. Thus, we decided to explore student engagement at UAB1 and UAB2 with these three components of our curriculum and how this engagement was influenced by students' NOS attitudes. As previously mentioned, we were unable to assess JSCC students using the ASPECT survey and interview questions due to limitations with allocated class time, but this information could nevertheless be gleaned from their end-of-semester interviews. We found that UAB1 and UAB2 students' average ASPECT survey responses ranked agar art > poster presentations > experimental design. Compared with experimental design, the agar art and poster presentations were reported as having more "value" (27), inclusive of being more fun, more productive, and more stimulating. In addition to being relevant for educators who use agar art in their pedagogies, these data also suggest that the students preferred and were most stimulated by assignments they may have deemed lower stakes and more creative. While some students did not immediately see the relevance of the agar art or may have not gotten the pictures they expected (Table 2, student quote d), many of them reported that agar art was a low-stakes and fun creative outlet (Table 2, see student quotes a, b, and c). Likewise, students liked the poster presentations, especially because they helped them learn what all the other students in the class had been working on (Table 2, student quotes h and i).

Compared to poster presentations, students felt the experimental design activity was less helpful for stimulating interactions between students, their peers, and their instructors. This is not to say the experimental design did not have value to the curriculum; from the student's perspective, without the research aspect, there would have been no improvements in sense of scientific efficacy (Fig. 2B), and students seemed to appreciate this fact based

TEXT BOX 3. Representative student quotes.

Lowercase letters correspond to parenthetical codes in Table 2.

Student quotes about agar art:

a. I'm not artistic at all but I enjoyed it more than I thought I would. (UAB2 student during interview 1.)
b. The idea is interesting, to see how the bacteria interact with each other. I think that's cool. We can make a prediction about them. You can look at dirt, or, you know, bacteria to make art and kind of get a better understanding. The art can teach you. And I think the art makes it more personable. (UAB2 student during interview 1.)
c. The concept of petri dish art is kind of cool. Never done it before. I liked that you could control what colors the art would be depending on what the [bacterial] color is. (UAB1 student during interview 1.)
d. Right, and so when we did the art, trying to touch it to a stick to get a little of it to rub off onto the plate didn't do anything. There was not growth, no observable—nothing to observe there. It just looked like it got killed off by the other bacteria. (UAB2 student during interview 3.)
e. I mean the art was fun but it was interesting, too. Anything, looking at the urease or methyl red, anything that was supposed to have a color change. That was nice because it was easy to see. (JSCC student during postinterview.)

Student quotes about designing experiments:

a. I liked getting to design my own experiment. Think about all of the stuff we had to do to make it work and carrying it through the presentation stage was pretty cool. We were fully invested in our own research for a couple weeks to the final stage. What about it made you like it? It was kind of creative. I guess to compare it to the lab in our other experiments or other labs where you do stuff out of a notebook, where it doesn't seem like you're doing something particularly notable and just following instructions, whereas you designed an experiment here and applying your knowledge to create. It's a different kind of challenge. (UAB1 student during interview 3.)
b. I really enjoyed the fact that we were really able to design our own lab. For the very last lab we did, we designed our own. So, we got to pick what we wanted to do, we got to have a hypothesis, and then test our hypothesis, and everything was in our own—like we got to choose it, so that was actually pretty interesting because then you're putting all the pieces together throughout what we had done, you know? To decide what you wanted based on what you had found interesting. (JSCC student during postinterview.)

Student quotes about poster presentations:

a. I think doing the presentation helped me understand the last experiment. When we started out, I was kind of like, I'm not sure, like, I don't know, we were just making something up to do. By the time we got through with the presentation, I was like, okay this actually sounds like real science. (UAB1 student during interview 3.)
b. I liked the presentations. Everybody actually got to work on communicating their findings instead of just coming here and doing the experiment and then churning it out, it actually helped in understanding because they had to verbally communicate it to us. (UAB2 student during interview 3.)

on their interview responses (Table 2, student quote f). It is possible that immediately following the process of having to design an experiment with their teams, students may have understood the relevance of the task but not its value, which only became evident weeks later after actually completing their experiments. Though some students reported enjoying the process of designing experiments, other students reported negative feelings related to performance, specifically feelings of under preparation or intimidation (Table 2). The open-ended nature of the assignment, and the lack of obvious success or failure metrics associated with an activity that was emphasized as central to the course, may have caused some UAB students to equate their uncertainties of experimental design with uncertainties about their overall success in the course. It seems that by the end of the semester, though, many of these concerns had been alleviated (Table 2). We suggest that CURE courses with experimental design aspects central to student success should include detailed rubrics for the experimental design step in an effort to alleviate some of these concerns by providing more concrete and immediate feedback on performance in this key activity.

When comparing UAB1 and UAB2, we found that the lowest overall ASPECT survey scores were from the UAB2 class during the experimental design activity (Fig. 3). In interviews, both UAB1 and JSCC students reported the experimental design activity being enjoyable and productive (Table 2, student quotes f and g), whereas similar comments were conspicuously absent from UAB2 interviews. A major difference between UAB2 and the other classes was that in UAB2, the CURE implementer did not directly oversee what happened in the laboratory classroom, whereas the opposite was true for UAB1 and JSCC. We thus suggest that a CURE's success may be strongly influenced by the laboratory instructor's level of engagement with, and investment in, the CURE pedagogy. Huffmyer and Lemus (38) have shown that instructor mindsets can impact student mindset in research laboratory courses. Likewise, recent work by Esparza et al. (39) showed that interactions between instructors and students play a pivotal role in student attitudes about science. Of the three activities we assessed, experimental design may have the lowest level of intrinsic entertainment value, and so it is possible that its success was critically dependent on direct involvement of a CURE-implementer instructor with direct oversight of the laboratory classroom who could emphasize and contextualize the CURE's value.

We failed to detect any correlations between ASPECT and NOS. It may be the case that our methodology failed to capture true relationships between these variables, possibly due to lower participation in the midsemester ASPECT surveys relative to that for the pre- and postsurveys. Alternatively, it may be the case that NOS gains were not realized until the end of the semester, after students had been impacted by all three activities. We also did not find that outcomes were tied to demographic variables such as race and sex, despite having substantial student diversity in all three classes (see Table S1 in the supplemental material). We found a similar lack of influence of demographic groupings in our previous work (18), suggesting our CURE may be useful for increasing the accessibility of research opportunities for traditionally underrepresented groups (40).

The Art of Microbiology may be relevant for community college-targeted CUREs

The central unifying goal for our curricular efforts with The Art of Microbiology was to create a portable CURE curriculum that is accessible to non-research-oriented institutions such as community colleges. While our results are especially relevant for those who use The Art of Microbiology curriculum or use agar art in their microbiology laboratory classrooms, this work is also part of a broader conversation on how specific aspects of a CURE class impact student outcomes, especially across diverse student populations with different instructor implementations. We recognize that community colleges are especially vital in their role in postsecondary education given nearly half of all postsecondary students are enrolled in, or have attended, community college (34). Despite this, community colleges are understudied in the biology education literature (41). For instance, Ballen et al. (42) developed a working group to address needs for CURE implementation in nonmajor biology classrooms at 4-year universities, including learning goals, research priorities, and collaboration needs, but to our knowledge, there are no directly comparable directions for CUREs in community colleges. Related, many students at community colleges leave their school without having authentic research experience (34), which could negatively impact their attitudes about NOS or their likelihood to pursue research either later in their educational process or as a career. There are efforts to rectify these gaps such as the Community College Undergraduate Research Initiative (CCURI) and other similar community college initiatives (34, 43), but there remain substantial logistical barriers for community colleges that want to offer student research experiences. We faced several of these barriers in using and assessing The Art of Microbiology CURE at JSCC, such as lack of an in-house IRB for administrative oversight of educational research (we were approved to work at JSCC through UAB), lack of institutional laboratory resources, and less administrative financial support. These problems were not unique to us; in fact, in the call to action by Schinske et al. (41), the authors recognized countless other constraints to community college CURE efforts. Importantly, Schinske et al. (41) lay out many support strategies for overcoming these constraints. Our efforts at JSCC were enabled by financial support from a National Science Foundation research coordination network and the UAB-centered research on stem education (ROSE) network, and we remain hopeful that funding agencies will strengthen such efforts as a way to increase research opportunities at the community college level.

Limitations

Our study may have been influenced by uncontrolled confounding variables, such as the effect of semester (spring versus fall) and specific student experiences in their accompanying lecture courses. While the strength of this study was the assessment of students in different instructors' classrooms, there was no direct replication of each class to determine if the effect of the instructor outweighed the effect of a specific student cohort, and there was no control where The Art of Microbiology was not used with the same instructor set. Also, though differences were detectable, the overall sample size ($n = 83$) may be considered low. Moreover, though it is possible that UAB1 and UAB2 student changes in three interval surveys reflect increasing student familiarity with surveying, we attempted to account for this potential limitation by also having qualitative interviews following the surveys to corroborate results. Lastly, we were limited in our direct comparisons between our university and community college students, because the JSCC students had differing course experiences beyond the three major activities and did not provide ASPECT data or interval interviews.

Conclusion

Our work shows that students report high engagement with agar art in an art-infused introductory CURE microbiology curriculum. Our curriculum, The Art of Microbiology, which is portable between instructors and institutional types, can stimulate gains in students' appreciation of NOS and their own scientific efficacy. More broadly, these results support and broaden the justifications for continued implementation and assessments of CUREs in 4-year research institutions but also in community colleges.

We began this article with a quote by E. O. Wilson from "Consilience: The Unity of Knowledge" (1). As we have shown that scientific questions can be born from art, and also that this art-infused pedagogy promotes student scientific outcomes, we return now to the words of Wilson: "the right answer to a trivial question is also trivial, but the right question, even when insoluble in exact form, is a guide to major discovery. And so, it will ever be in the future excursions of science and imaginative flights of the arts." Paraphrased in the words of a student from UAB2: ". . .the art can teach you."

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, DOCX file, 0.9 MB.

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