INQUIRY & INVESTIGATION

A Model of Science, Technology, Engineering, and Mathematics Remote Research-Based Learning: High School Independent Authentic Research Experiences from Home

SANDRA ARANGO-CARO, KAITLYN YING, ISABEL LEE, KATHRYN PARSLEY, KRISTINE CALLIS-DUEHL

Abstract

Opportunities for research-based learning at the high school level are limited, and with the COVID-19 pandemic, these have been further reduced. Such opportunities are particularly scarce for authentic research experiences (AREs), which allow students to identify as scientists by collecting data that contributes to scientists' research. In response to the COVID-19 pandemic, we adapted two of our AREs for classroom settings, as remote independent research experiences for students to conduct from home. User guides and protocols from the AREs, Genotype-to-Phenotype Research with Corn and Discover Volvox Development, were adapted to instruct high school students to work on their own with the guidance of scientists and ARE coordinators. These independent authentic research experiences (IAREs) were implemented in the summer of 2020 and have since been available to students. Student responses to reflection questions and the Laboratory Course Assessment Survey indicate that IAREs provide students with significant gains including learning science content and research practices, collaborating with scientists, facing and resolving challenges, and contributing to scientific research.

Key Words: *authentic research experiences; high school students; student independent research; learning gains.*

○ Introduction

To develop science literacy among students, it is necessary to develop knowledge and competency in science through high-quality learning experiences that encourage active participation using tools and practices that lead to scientific experimentation and discovery (National Academies of Sciences, Engineering, and Medicine [NASEM], 2021). Authentic research experiences (AREs) allow students to learn science in a way that reflects how science works and do the things that scientists do. In AREs, the outcome of the investigation is open, as it involves the contribution of student-determined data to scientist-led research programs, bridging the gap between research and teaching (Bennett et al., 2018; Krim et al., 2019; NASEM, 2021). These experiences allow students to engage with scientific phenomena, participate in the design and development of scientific investigations, discuss ideas with others, and make connections to real-world problems and current scientific issues (NGSS Lead States, 2013; Kitchen et al., 2018; NASEM, 2021).

At the high school level, benefits from research activities include gains in disciplinary content knowledge and science practice, intellectual development, self-confidence, and communication skills (Bell et al., 2003; Sadler et al., 2010; Kitchen et al., 2018; Mastronardi et al., 2020; Puslednik & Brennan, 2020; Corson et al., 2021). These benefits may result in a deeper interest in scientific disciplines that encourages students to enroll in college, partake in graduate studies, and pursue science, technology, engineering, and mathematics (STEM) career paths (Tai et al., 2017; Kitchen et al., 2018; Mastronardi et al., 2020; Wickliffe et al., 2020; NASEM, 2021).

One model for student AREs is through independent research work. Independent authentic research experiences (IAREs) involve student-led, open-ended investigations involving practical work (Bennett et al., 2018). IAREs allow students to be scientists, see themselves as scientists, and have a realistic research experience (Bennett et al., 2018). The IAREs allow students to work independently with the support of teachers or research mentors. When challenges arise, the students face them first on their own before asking for help. This exposure faces them with the realities of both research success and productive failure, leading to reevaluations of experimental design (Mastronardi et al., 2020). These experiences allow students to develop a greater sense of project ownership than when the project is conducted in groups under teacher supervision. The IAREs also support the interests of introverted students who may feel more comfortable working on their own, although students should still learn that collaboration and group work are essential to science research (Burgin et al., 2012).

AREs, however, are limited and not accessible to all high school students (Bennett et al., 2018; Kitchen et al., 2018; Mastronardi et al., 2020; NASEM, 2021). This is particularly true of students who have been underserved due to racial, rural, or socioeconomic factors, which limit access to apt resources for scientific engagement and leads to underrepresentation in STEM (Puslednik & Brennan, 2020; Witzel et al., 2020). Thus, collaborations between schools, both K–12 and higher education, and research institutions are necessary to strengthen and diversify STEM pathways and STEM education (Kitchen et al., 2018; Puslednik & Brennan, 2020). These collaborations can result in opportunities that expand the learning of science through internships, apprenticeships, and foundational research experiences (NASEM, 2021). These experiences allow

The American Biology Teacher, Vol. 86, No. 1, pp. 24–29, ISSN 0002-7685, electronic ISSN 1938-4211. DOI: https://doi.org/10.1525/abt.2024.86.1.24.

students to have research learning experiences outside the classroom environment that offer opportunities to interact directly with scientists, work at high-end research facilities, and expand their networks of future mentors.

The Education Research and Outreach Laboratory (EROL) at the Donald Danforth Plant Science Center (DDPSC) in St. Louis, Missouri, generates and facilitates AREs that are linked to DDPSC research and align with NGSS standards. EROL works with educators across the country to bring these experiences to entire classes or to individual students as independent research projects, making special efforts to reach underrepresented groups. Professional development, curricula, materials, and scientific advice are offered at no cost. EROL also assesses student research experiences to investigate student learning gains.

In this article, we introduce two IAREs from EROL available to high school students and present their learning gains based on their implementation in the summers of 2020 and 2021, during the peak of the COVID-19 pandemic. During this pandemic, implementing hands-on AREs became a major challenge, especially during the summer (Corson et al., 2021). In 2020, in addition to the shift to remote classroom learning, after-school activities and summer camps were canceled due to their potential health risks associated with the pandemic. In the spring of 2020, high school students reached out to the EROL asking for summer research opportunities. EROL responded to this request by adapting two AREs that were offered in classroom settings to independent research projects from home, promoting scientific learning while minimizing in-person contact. These IAREs, Genotype-to-Phenotype Research with Corn (G2PC) and the Discover Volvox Development (DVD), offer remote research-based learning, allowing students to conduct research that contributes to the Danforth's scientific mission of "improving the human condition through plant science" while experiencing real-world applications of the scientific process in a way that is compatible with COVID-19 restrictions.

○ Methods

Independent AREs from Home

Genotype-to-Phenotype Research with Corn

Leaf angle in corn plants is an important phenotypic parameter when determining plant density (how many plants can be grown per acre) and yield (ears of corn produced per acre). Dr. Andrea Eveland, PhD, Principal Investigator at the Danforth Center, and her team investigate genetic factors that regulate corn phenotypic variation in leaf angle. In this IARE, students grow corn seedlings from different genotypes and measure their leaf angles manually and digitally using image analysis software. Students analyze the data to compare leaf angles across genotypes and between measurement methods. Eveland's lab uses student data for the development of predictive models that determine the leaf angle of adult plants based on seedling data. The G2PC activity allows students to learn concepts of genetics as they relate to agriculture, food security, and data science. See the Supplemental Material available with the online version of this article for a detailed description of this activity or visit the AREs website (are.danforthcenter.org/g2p.html).

Discover volvox development

The green algae *Volvox carteri* is an experimentally tractable multicellular species with recently evolved germ and somatic cell types (hereafter *V. carteri* will be referred as Volvox). Volvox is a visually engaging organism that students use to learn important lessons about organismal life cycles. This species is under investigation in the laboratory of Danforth Center Principal Investigator Dr. Jim Umen to understand the origins of multicellularity. In this ARE, students culture volvox and screen colonies for developmental mutants. Student findings contribute to discoveries of new mutants used in Dr. Umen's lab for the screening of genes that control mechanisms of cell division. The DVD activity allows students to learn concepts of evolution and organismal development. See the Supplemental Material available with the online version of this article for a detailed description of this activity or visit the AREs website (are.danforthcenter.org/dvd.html).

Student Recruitment

The EROL works with educators to bring AREs to their students. These educators present to their students the opportunity to conduct IAREs from home as an after-school or summer activity. Students also reach the EROL directly, after visiting the ARE website (are.danforthcenter.org). Interested students contact the ARE team (ARE@danforthcenter.org), who then provide the students with user guides and protocols so students can review the IARE's goals, content, and expectations. After the students confirm their interest in implementing an IARE, the ARE team follows up with them to implement the IAREs from home.

Implementation of IAREs from Home

Materials

The AREs coordinator works with each student to coordinate when and how to have materials delivered and return them as needed. See the Supplemental Material available with the online version of this article for a detailed description of the items provided by the Danforth and the students.

Project development

During the implementation of the IRAs in 2020 and 2021, the ARE coordinator facilitated the resources to implement the IAREs using Google Classrooms. Now, the EROL uses an ARE portal (are.danforthcenter.org) where students access protocols and worksheets, upload data (measurements, photos, and notes), and complete assessments about their experiences with the IAREs (see "Project support"). The students did not have the opportunity to contribute to the research design. However, they were allowed to adjust their experiments based on the challenges they were facing. For example, students used sticks to keep the plants straight, cleaned the plants from pests, adjust the phenotyping date based on how wide the leaves were opened, and so on.

Project support

The ARE coordinator and scientists resolve any questions the student may have through emails, Zoom meetings, and phone calls (e.g., procedure clarifications, organisms' performance, etc.).

Dissemination of IAREs data

Students can present their results during scientific and public events with the Danforth Center (e.g., scientific retreat, PlantFest) or specific conferences related to each IAREs (e.g., Annual Maize Genetics Meeting).

Assessment of Student Learning Gains

To assess the student learning gains of conducting IAREs from home, at the end of their projects, students complete written reflections and the Laboratory Course Assessment survey (LCAS) (Corwin et al., 2015) (available in the Supplemental Material online). Students also provide parental consent and student assent following IRB requirements (IRB_2020_08).

The written reflections pose questions about the motivation to conduct an IARE, learning expectations and outcomes, challenges, and memorable moments. Two members of the EROL qualitatively code the answers to the written reflection questions using the deductive coding method. This method uses a top-down approach to systematically categorize excerpts from students' responses based on recurring themes and patterns. The coders read the answers and assign excerpts to codes, building a codebook. The coders compare their codes and adjust them to create an agreed-upon qualitative code book. Frequencies and percentages of the codes are summarized by major themes aligned with the reflection questions.

The LCAS measures student perceptions of three dimensions of research-course design (collaboration, discovery, and iteration). The *collaboration* dimension (6 items) addresses how often students are encouraged to work together and provide and respond to feedback (scale: 1 = never, 2 = one or two times, 3 = weekly, 4 = monthly). The *discovery* dimension (5 items) describes the degree to which students had opportunities to generate new knowledge in the discipline. The *iteration* dimension (6 items) describes the degree to which students had opportunities to revise or repeat aspects of their work to address problems or new questions in order to improve the validity of their own and others' results. For *discovery* and *iteration*, a 6-point Likert scale is used (1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, 6 = strongly agree). The coders count the responses from each scale item in each dimension and convert them to percentages.

○ Results

Learning Gains from IAREs Implementation in 2020 and 2021

Participants

A total of 15 students from 11 schools participated in the IAREs during the summers of 2020 and 2021. Five students conducted the DVD project, five students conducted the G2PC project, and five students conducted both projects. The participants were students from nine public and two private schools from the St. Louis metropolitan area.

Results from written reflections

Written reflections were available from 11 students who assented, and whose parents had consented to the release of their responses. Student reflections are presented per question.

Question 1. Motivation: Why did you decide to participate in this independent research experience? Student motivation to join these IAREs (18 statements) included a personal interest in science (55.6%), as well as an interest in gaining research experience (27.8%), pursuing a scientific career (11%), and contributing to the scientific community (5.6%).

Question 2. Learning expectations: Prior to starting this research, what did you expect to learn? Student learning expectations (13 statements) included learning content related to specific activities, such as genetics concepts and knowledge of the corn and volvox organisms (61.5%). Other expectations were related to learning about the scientific method (15.4%), research practices and techniques (7.7%), the role of research scientists (7.7%), and the importance of studying a science subject (7.7%).

Table 1. Percentage of statements about fulfilled student learning expectations.

Statements of Fulfilled Learning Expectations	Counts	%*
Good learning experience, fun, and hands-on	7	23
Using equipment, including software	6	20
Application of scientific experimentation outside of school (how real scientists conduct experiments)	4	13
Working with the scientific method	4	13
Handling specimens (e.g., growing corn and identifying and isolating volvox colonies)	4	13
Learning scientific content	4	13
Collecting data	2	7

*Percentages do not add to 100% since a student could have mentioned more than one expectation in a statement.

Question 3. Fulfillment of learning expectations: Upon completion of the research, what did you learn? Did it meet your previous expectations? All students reported that their research experiences fulfilled their expectations (31 statements) (Table 1).

The following quotes are examples of students' responses on the fulfillment of their learning expectations. This type of statements were coded to generate the results in Table 1.

> I learned a lot about how to use equipment, and how to do research.

> I learned how to take good notes and make specific observations, and I learned how to draw conclusions from results.

> I learned how to care for the corn seedlings and how to work with [the image analysis survey], and I could make connections with how different genotypes of corn I planted grew healthier or weaker seedlings.

> I learned how to screen and identify certain Volvox colonies, as well as better understand their significance in studying the origins of multicellularity.

Question 4. Challenges: Describe a challenge(s) you experienced during this independent research project. How did you overcome the challenge(s) you faced during this independent research project? Based on 20 statements, many students referred to difficulties handling specimens (40%), mostly growing the corn seedlings and few isolating volvox individuals. Students expected to have 100% germination and growth, but they realized that not all seeds were necessarily viable and that seedlings could have unhealthy growth, even if the proper care was provided. A clarification about these expectations was made in an updated version of the G2PC protocol. Another difficulty involved using equipment and/or software (25%). Most of the statements were related to the use of the imaging software PlantCV for the G2PC project in 2020. PlantCV was replaced in 2021 with a more user-friendly software, ImageJ. A few statements were about focusing the microscope. Other challenges reported (35%), were time constraints for collecting the data, unclear instructions for manipulating the volvox, and inconclusive results.

The students overcame scientific challenges by contacting the ARE coordinator for advice and repeating or adjusting their experiments. Students ran the image analysis software several times, adjusted the corn plants' environmental conditions, and removed pests.

Question 5. Memorable moments: Please share a memorable moment from your independent research project experience. What made it memorable? Most of the memorable moments were related to handling and observing the specimens. For the G2PC activity, students reported memorable moments while observing the germination of the corn seeds, successfully growing the seedlings, and measuring their leaf angles. Some quotes from the students are:

> It was very exciting to see more seedlings start to grow and know that I was on the right track.

> When the corn seedlings first sprouted, I was ecstatic!

> For me to have grown them all by myself was really exciting and encouraging.

In the DVD activity, memorable moments included the successful viewing and isolation of the volvox and using the microscope. These are some quotes from the students:

> It was really exciting when I got the stereoscope to focus and I could see all the little colonies in their own little world.

> I couldn't even stop the gasp of triumph coming from my mouth when I finally viewed the tiny, green cells.

The student reasons for experiencing memorable moments included gaining new and interesting experiences and perspectives, experiencing the ability to overcome challenges or uncertainties, enjoying the self-directed nature of the research experiences, having fun, and experiencing productive failure.

Results from the LCAS

Ten students completed the LCAS that measures students' perceptions of three design features of biology lab courses: (1) collaboration, (2) discovery, and (3) iteration.

Collaboration (Figure 1). The IAREs provided limited opportunities for collaboration due to their nature as independent experiences conducted from home, especially as they were initiated as remote research opportunities during the COVID-19 pandemic. However, 40%–60% of the responses indicate that students had opportunities of collaboration, through interactions with scientists and the ARE coordinator, at least one or two times, or more. Students recommended future opportunities to interact with the other participating students remotely.

Discovery (Figure 2). Students acknowledged opportunities for discovery by explaining how their work resulted in new scientific knowledge developing new arguments based on data (50%–60% agree to somewhat agree). They also acknowledge formulating their own research questions or hypotheses (50%–60% strongly agree to somewhat agree). Other responses showed that students acknowledge conducting research that had previously been unknown to them and generating novel results of interest to the broader scientific community (80%–90% strongly agree to somewhat agree).

Iteration (Figure 3). Students had few opportunities to revise drafts of papers or presentations soon after their IARE experience was over. However, the students were able to revise or repeat analyses and collect and analyze additional data (70% strongly agree to somewhat agree). Other responses indicate that students were able to share and compare data with others (70% agree to somewhat agree), as well as change methods and revise or repeat work (85%–90% strongly agree to somewhat agree).

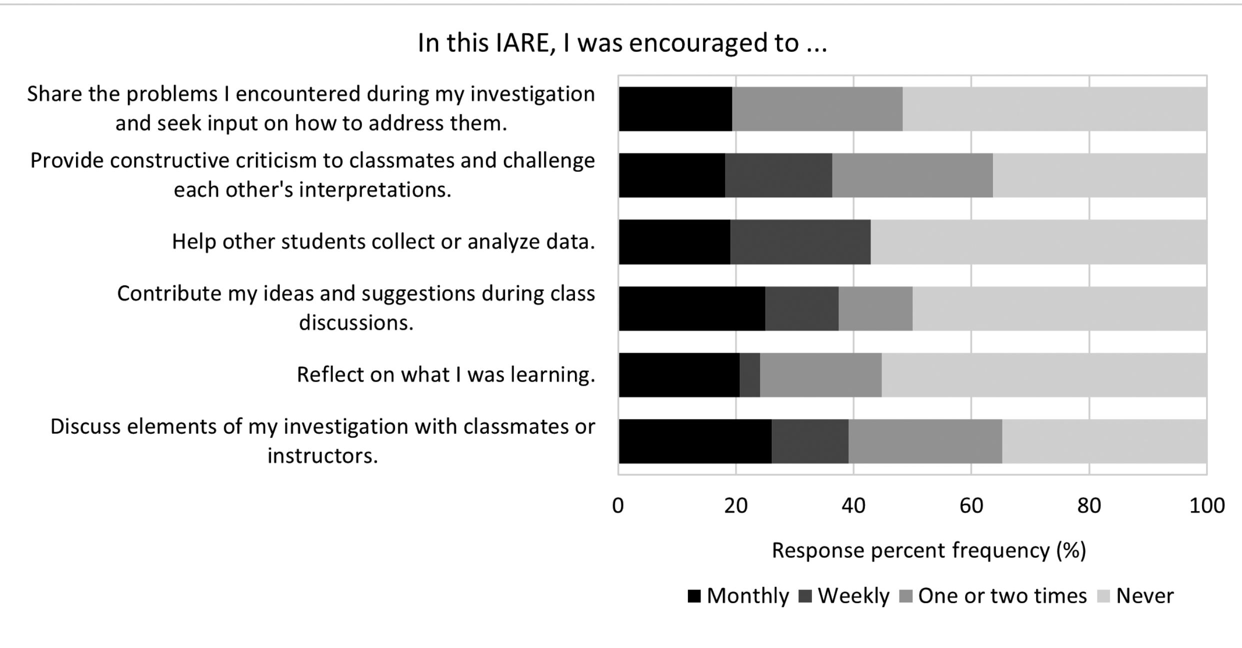

Figure 1. LCAS results for the collaboration dimension of IAREs.

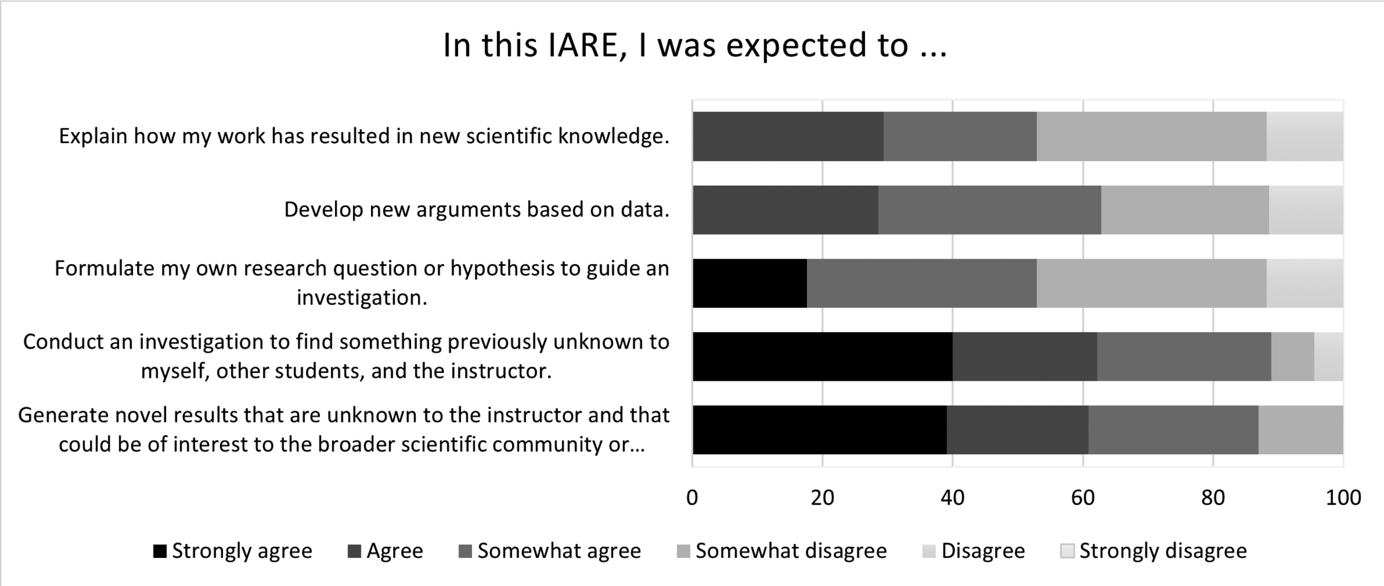

Figure 2. LCAS results for the discovery dimension of IAREs.

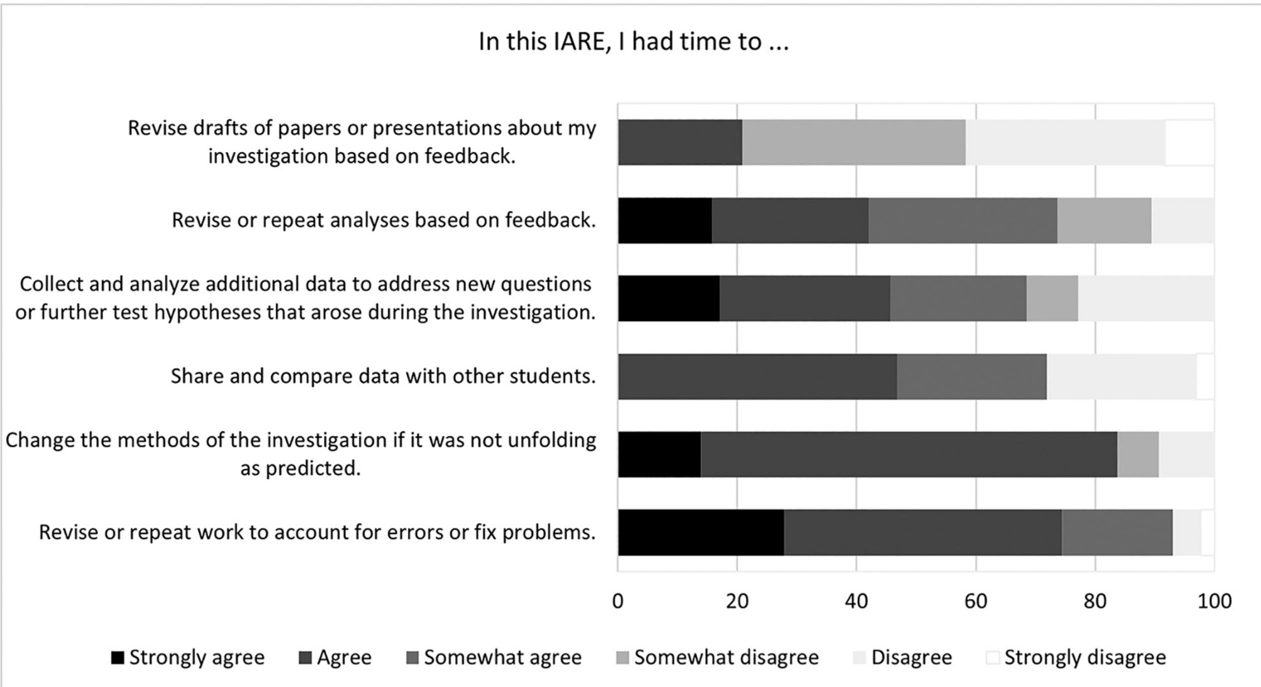

Figure 3. LCAS results for the iteration dimension of IAREs.

○ Conclusions

Implementation of the IAREs

Students provided positive feedback about the planning and execution of the projects. Students suggested making improvements by making the protocols more detailed and clearer (DVD) and informing of potential challenges when conducting the activity.

Benefits for the Students

Students acquired STEM knowledge and skills by conducting IAREs. They found the IAREs to be enjoyable experiences that kept them busy and allowed them to experience research in the making. They completed the projects successfully because they followed the instructions, collected and shared the data requested, and returned the materials in optimal conditions in a timely manner, including expensive stereoscopes. This demonstrates that high school students can assume the responsibility to conduct their own research projects. One student highlighted that the IARE allowed her to have "control" of the whole project, rather than doing only a part of a project when working with other students and with teacher involvement. All of the responsibility of the project fell on the students, which helped them increase their self-confidence and identify more as scientists.

Some students continued to be involved with the EROL. Two students from the 2020 cohort joined the EROL, first as volunteers and then as paid interns. Both are currently undergraduate biology majors. One student worked with the lab for a year and a half, and the other student is a continuing intern. We are proud to point out that they are coauthors of this publication (Ying and Lee). Two other students from the 2020 cohort participated in summer internships in 2021–2023. with other research labs at the DDPSC.

Some students had the opportunity to present their projects at scientific conferences practicing their communication skills. Three students from the 2020 cohort and one from the 2021 cohort presented their projects at the Life Discovery Conference from the Ecological Society of America, the Environmental Education Conference from the Missouri and Kansas Environmental Education Associations, and the Maize Genetics Meeting.

The student and co-author, Isabel Lee, decided to continue with her project by designing a follow-up experiment for a course she took at school on independent science research. This project, "Ideal Time of UV Light Exposure for Efficient Production of gls *Volvox carteri* Mutants," received two awards during the Academy of Science – St. Louis science fair in 2021.

Benefits for Teachers

The DDPSC generates and facilitates professional development, learning experiences, instructional materials, and supplies at no cost that are aligned with the NGSS. These are responses to the challenges that science education faces in the United States, where there are limitations to supporting high-quality science learning, teachers' overload, and budget restrictions (Bennett et al., 2018; NASEM, 2021). By supporting students to conduct IAREs, educators are supporting the development of student science identity and interest in future STEM careers. The DDPSC continues the development of new AREs with the option to be IAREs.

○ Acknowledgments

The authors thank the participating students who contributed data to Danforth plant and education research. Doctors Jim Umen, Jiani Yang, Andrea Eveland, Sa Geng, and Minglu Gao designed the experiments of the AREs. The Genotype-to-Phenotype Research with Corn project was funded by the NSF Award # IOS-1733606. The Discover Volvox Development project was funded by the NSF Award # 1755430.

References

Bell, R. L., Blair, L. M., Crawford, B. A., & Lederman, N. G. (2003). Just do it? Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching*, *40*(5), 487–509. https://doi.org/10.1002/tea.10086

Bennett, J., Dunlop, L., Knox, K. J., Reiss, M. J., & Torrance Jenkins, R. (2018). Practical independent research projects in science: A synthesis and evaluation of the evidence of impact on high school students. *International Journal of Science Education*, *40*(14), 1755–1773. https://doi.org/10.1080/09500693.2018.1511936

Burgin, S. R., Sadler, T. D., & Koroly, M. J. (2012). High school student participation in scientific research apprenticeships: Variation in and relationships among student experiences and outcomes. *Research in Science Education*, *42*(3), 439–467. https://doi.org/10.1007/s11165-010-9205-2

Corson, T. W., Hawkins, S. M., Sanders, E., Byram, J., Cruz, L. A., Olson, J., Speidell, E., Schnabel, R., Balaji, A., Ogbeide, O., Dinh, J., Hinshaw, A., Cummings, L., Bonds, V., Nakshatri, H. & Nakshatri, H. (2021). Building a virtual summer research experience in cancer for high school and early undergraduate students: Lessons from the COVID-19 pandemic. *BMC Medical Education*, *21*(1), 422. https://doi.org/10.1186/s12909-021-02861-y

Corwin, L. A., Graham, M. J., & Dolan, E. L. (2015). Modeling course-based undergraduate research experiences: An agenda for future research and evaluation. *CBE: Life Sciences Education*, *14*(1), es1. https://doi.org/10.1187/cbe.14-10-0167

Kitchen, J. A., Sonnert, G., & Sadler, P. M. (2018). The impact of college- and university-run high school summer programs on students' end of high school STEM career aspirations. *Science Education*, *102*(3), 529–547. https://doi.org/10.1002/sce.21332

Krim, J. S., Coté, L. E., Schwartz, R. S., Stone, E. M., Cleeves, J. J., Barry, K. J., Burgess, W., Buxner, S. R., Gerton, J.M., Horvath, L., Keller, J. M., Lee, S. C., Locke, S. M. & Rebar, B. M. (2019). Models and impacts of science research experiences: A review of the literature of CUREs, UREs, and TREs. *CBE: Life Sciences Education*, *18*(4), ar65. https://doi.org/10.1187/cbe.19-03-0069

Mastronardi, M., Boklage, A., Hartman, R. D., Yañez, D., & Borrego, M. J. (2020). Impact of a summer research program for high school students on their intent to pursue a STEM career: Overview, goals, and outcomes. In *2020 ASEE Virtual Annual Conference Content Access Proceedings* (p. 34751). Virtual Online: ASEE Conferences. https://doi.org/10.18260/1-2--34751.

National Academies of Sciences, Engineering, and Medicine. (2021). *Call to Action for Science Education: Building Opportunity for the Future*. In M. Honey, H. Schweingruber, K. Brenner, & P. Gonring (Eds.). National Academies Press. https://doi.org/10.17226/26152

NGSS Lead States (Ed.). (2013). *Next Generation Science Standards: For States, By States*. National Academies Press.

Puslednik, L., & Brennan, P. C. (2020). An Australian-based authentic science research programme transforms the 21st century learning of rural high school students. *Australian Journal of Education*, *64*(2), 98–112. https://doi.org/10.1177/0004944120919890

Sadler, T. D., Burgin, S., McKinney, L., & Ponjuan, L. (2010). Learning science through research apprenticeships: A critical review of the literature. *Journal of Research in Science Teaching*, *47*(3), 235–256. https://doi.org/10.1002/tea.20326

Tai, R. H., Kong, X., Mitchell, C. E., Dabney, K. P., Read, D. M., Jeffe, D. B., . Andriole, D. A. & Wathington, H. D. (2017). Examining summer laboratory research apprenticeships for high school students as a factor in entry to MD/PhD programs at matriculation. *CBE: Life Sciences Education*, *16*(2), ar37. https://doi.org/10.1187/cbe.15-07-0161

Wickliffe, J.L., Coates, T., Rodas, J., Pomeroy, M., Carrillo, U., Luaces, M.A., Twillman, N., Ilabaca-Somoza, X., Meyer, M., Harlan-Williams, L., Ramaswamy, M. (2020). Description of a 20-yearlong initiative to bring STEM career exploration to urban minority youth in Kansas City, Kansas: Multisector investment and program evolution. *Journal of STEM Outreach*, *3*(2), 1–13. https://doi.org/10.15695/jstem/v3i2.04

Witzel, L., MacCormack, J., Nielsen, K., & Smith, R. (2020). Fostering pathways: 30 years of inspiring high school students to pursue science careers through biomedical research experiences. *Journal of STEM Outreach*, *3*(2), 1–14. https://doi.org/10.15695/jstem/v3i2.01

SANDRA ARANGO-CARO (sarango-caro@danforthcenter.org) is a senior education researcher and program manager. KAITLYN YING (kying@danforthcenter.org) is an undergraduate intern. ISABEL LEE (isalee086@gmail.com) is a former high school intern and KATHRYN PARSLEY (parsley@wustl.edu) is a former postdoctoral fellow, all in the Education Research and Outreach Laboratory at Donald Danforth Plant Science Center (DDPSC), St. Louis, MO 63132. KRISTINE CALLIS-DUEHL (kcallisduehl@danforthcenter.org) is the Executive Director of Education Research and Outreach at DDPSC.