An Integrated Secondary School STEM Research Program: Results, Challenges, and Opportunities

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Abstract – **Numerous models exist for secondary school research programs, from summer extra-curricular programs lasting one or two weeks to more extended programs based in a student's school. The degree to which a research program is integrated into the culture and curriculum of a school may have a significant effect on the learning outcomes of the program. In this paper, we present survey results from a cohort of 44 students in a school-based, integrated STEM research program in which students complete a two-year, on-campus research project in a discipline of their choosing. Paired sample t-tests were used to test for differences between student responses following the 2017 and 2018 academic years. The results indicate statistically significant gains in dimensions such as understanding the nature of science, research skills, feeling part of a scientific community, and their likelihood of pursuing advanced degrees in STEM fields. In addition, we test for differences between juniors (one year in the research program) and seniors (two years) to determine there are significant gains associated with the second year of the program. The results of this comparison were non-significant and may suggest diminishing returns in the second year of the research experience. However, small sample sizes may have limited the power of this comparison; seniors do report higher gains than juniors in all variables measured across both years. The unique advantages, challenges, and opportunities associated with this integrated model of a secondary school research program are discussed, with particular attention to the role of internal mentors, the length of the research experience, and the relationship of the research program to school culture.**

Index Terms - length of research experience, research mentors, school culture, secondary school, STEM research programs

INTRODUCTION

Authentic research experiences for secondary school students are effective at achieving the learning goals of STEM education such as understanding of discipline content, development of research skills, confidence, and intellectual development, and influence on career aspirations [1]–[6]. While some students may participate in summer research programs or find independent opportunities, many students find research experiences through a program at their high school [1], [5], [7]. School-based STEM research programs come in a variety of forms and it is likely that many organizational factors of these programs influence the quality of the research experiences and their pedagogical effectiveness. In particular, the degree to which the research program is integrated into the school's culture and curriculum may be important. For example, whether mentors are internal to the school (typically teachers that may have already taught the students) or external (typically from universities or private organizations) can have a significant influence on the quality of the mentor-mentee relationships, an important variable for the learning outcomes associated with authentic research experiences [1], [4], [8]–[10]. Integration of a research program also encompasses numerous other factors such as the length of the research experience, whether participation is required or not, and the number of disciplines in which a student can pursue research. In this article, we present survey results from a school-based research program at Princeton International School of Mathematics and Science (PRISMS) and discuss the advantages and disadvantages of this model.

PRISMS CURRICULUM AND RESEARCH PROGRAM

Princeton International School of Mathematics and Science is a small international boarding school consisting of predominantly Chinese and American students (82 students currently). As the name implies, the curriculum is heavily math and science focused. Notable aspects of our curriculum are the two years of applied engineering taken by freshman and sophomores, the requirement of two science courses by freshman (biology and the choice of chemistry/physics), and the requirement of two AP STEM courses by sophomores. The strong foundation that freshman and sophomores receive in STEM disciplines is designed to prepare them for the required two-year STEM research project that they complete as juniors and seniors.

The research experience at PRISMS starts with the semester-long BASE project (Bridging the Arts through Science and Engineering) completed during the second semester of freshman year. In brief, students work in pairs to test how a variable of their choosing affects the growth and development of kale plants. Students are required to build and calibrate a sensor that allows them to collect quantitative data (on variables such soil pH or moisture, UV radiation, or temperature), write a complete scientific article, and give a

15-minute presentation on their experiment. The BASE project is a collaboration between biology, engineering, and English and work on the research project takes places in all three classes.

As sophomores, students focus on developing content knowledge and research skills in AP courses and begin to think about areas of interest for their research project. Beginning in February, sophomores begin a series of lab rotations where they meet with lab directors to learn about the research in the lab, discuss potential projects, and assess whether or not they will be a good fit in the lab. This culminates with the writing of a short proposal in April and the placement of students into research labs in May.

Research mentors are constrained by their knowledge, equipment, resources, and the interests of their students, but within those constraints freedom is given to develop projects as they see fit. The goal is for every project to be an authentic open-ended inquiry where skills, knowledge, and confidence are developed throughout, however the degree to which this goal is achieved will vary for each student because each project is unique. There are some projects where the student contributes substantially to the original conception and planning. In other cases, the student continues a pre-existing project or research direction. We find that it is almost always possible to work with student interests and ideas to some extent when developing a project.

Students are expected to participate in all aspects of the inquiry process throughout their research project — generating research questions, experimental design, data analysis, and communicating results. Given the diversity of subjects in which students can pursue research (see Table 1), the day-to-day nature of the work varies considerably between students. Limitations on time, resources, and student knowledge can cause mentors to be more or less hands-on at different stages in the process, but the general aim is for students to do as much of the actual research as possible.

TABLE 1

SELECTED TOPICS OF STUDENTS' RESEARCHES FROM 2017-2018

Students' Research Topics
Paper-based Mercury Detection Implementing Gold Nanoparticles and Mercury-specific Oligonucleotide
Tourist Behavior Analysis: Identification and Classification
Design and implementation of mobility system for the multifunctional underwater robot
Development of an easy-to-use, paper-based sensing device for colorimetric detection of formaldehyde
Reconstruction of Ancestral Tumor Necrosis Factor-Alpha
Color making and characterization from BnF Ms. Fr. 640
Evolutionary Analysis of RNA Editing in Cephalopods
Supported-Peptide Filter for Arsenic

All major STEM disciplines are represented with research labs [11]. In 2016-2017, the research labs were molecular biology, materials chemistry, analytical chemistry, physics, nanotechnology, data science, artificial intelligence, engineering, math, and mathematical modeling. In 2017-2018, two additional labs were added — computational biology and optics. A psychology lab has been added for the current 2018-2019 school year.

Juniors and seniors have a research period totaling 3.5 hours of time per week and 120 hours for an academic year. Grades are assigned for research; however, expectations and assessments are left up to the lab directors and thus vary between students working in different labs. At the end of every semester, there is a "Research Day" where every student is required to give a presentation (30-minute time slot) or present a poster during a school-wide poster session. Juniors give a presentation after their first semester of research and present a poster at the end of the year; for seniors, this is reversed, and they end with the presentation. The final requirement for the research project is a written report that all seniors complete by the end of the year. Students often submit posters and papers to competitions and fairs; however, this is not a requirement.

RESEARCH QUESTIONS

During the final exam week of the 2016-2017 and 2017-2018 school year, the URSSA (Undergraduate Research Self-Assessment Survey) was taken by all students at PRISMS in order to evaluate learning outcomes from the research program [12], [13]. Five independent variables were assessed with the survey results: (1) gains in thinking and working like a scientist (WIS); (2) personal gains related to research work (PG); (3) gains in skills (SKILL); (4) attitudes or behaviors as a researcher (ATT), and (5) career and graduate education aspirations (INF). Our research questions are generated from these five variables.

(1) Are there statistically significant differences between students' responses to WIS, PG, SKILL, ATT, and INF from students in 2017 (sophomores and juniors) and the students in 2018 (juniors and seniors)?

(2) Are there statistically significant differences between junior and senior responses to WIS, PG, SKILL, ATT, and INF from the same year?

METHODS

All 82 students at PRISMS (first-year freshmen through fourth-year seniors) participated in the survey in 2017 and 2018. The survey was administered at the end of the year after all research activities. Freshman surveys in both years were excluded from analysis because they do not participate in the research program. One student sequentially chose 1-2-3-4-5 as he went through the questions and this student's survey was excluded. The final population of the research study was 44, including 16 sophomores (11 males and 5 females), 20 juniors (13 males and 7 females), and 8 seniors in 2017 (6 males and 2 females). All sophomores and juniors in 2017 took the survey again as juniors and seniors in 2018 and thus allow for matched-pair statistical analysis. In total, 36 students were included in the matched pair analysis (the 8 seniors in 2017 were not included in this analysis because they graduated). All students were assigned an ID number for the initial survey in 2017 and are anonymous to the authors of the paper.

TABLE 2
DISTRIBUTION OF THE RESEARCH STUDENTS IN 2017

	Sophomores	Junior	Senior
Male	11	13	6
Female	5	7	2
Total	16	20	8

As previously mentioned, PRISMS conducted a pilot implementation of the URSSA online survey during the final exam week of the 2016-2017 school year. All questions from the online survey were adopted with permission from the URSSA team. The URSSA survey was modeled on the SALG (Student Assessment of Their Learning Gains) instrument, with an emphasis on student reports of their own learning gains in cognitive, behavioral, and affective areas [13]. Students are required to answer 134 questions grouped in 17 blocks from the survey. In terms of students' learning outcomes, there are 8 dependent variables describing WIS, 6 dependent variables describing PG, 12 dependent variables describing SKILL, and 8 dependent variables describing ATT. Regarding INF, there were some questions which were not relevant for high school students and thus we excluded these from further analysis. At the end of the 2017-2018 school year, PRISMS again organized the same assessment. This research study used these two years of data for analysis.

After the data from 44 participants were collected, the IBM SPSS 18 package was used to process the data. Two primary statistical methods in the package were used in this paper. First, paired sample t-tests was designed in this study to compare responses from the same students in different years. We used μ_d to depict the mean difference of students' responses to their learning outcomes (responses in 2018 minus responses in 2017). We, therefore, wanted to test the hypotheses $H_0\colon \mu_d = 0$ and $H_a\colon \mu_d \neq 0$. Second, a Mann Whitney U test was conducted to compare different students' responses in the same years. We wanted to test $H_0\colon \mu_j = \mu_s$ and $H_a\colon \mu_j \neq \mu_s$,where μ_j and μ_s were the true mean of juniors and seniors respectively.

RESULTS

The descriptive statistics for the five independent variables are shown in Table 3. The mean values of all variables were higher in 2018 than in 2017, indicating that the scores of students' responses increased in general. All variables roughly followed the normal distribution. For instance, the Q-Q plots in Figure 1 indicated that the WIG2017 plot looked very linear, while the WIG2018 plot showed some slight curvature. Neither plot had strong outliers or clear skewness. Individual observations of each variable were independent.

TABLE 3
DESCRIPTIVE STATISTICS OF INDEPENDENT VARIABLES

	N	Mean	Std. Deviation
WIS2017	44	30.7045	8.34873
WIS2018	36	39.9773	9.1359
PG2017	44	33.1364	9.05947
PG2018	36	40.9545	11.90848
SKILL2017	44	50.0455	13.61763
SKILL2018	36	62.8636	18.74876
ATT2017	44	27	9.40064
ATT2018	36	35.4318	13.53445
INF2017	44	7.8864	4.44719
INF2018	36	12.1818	8.0066

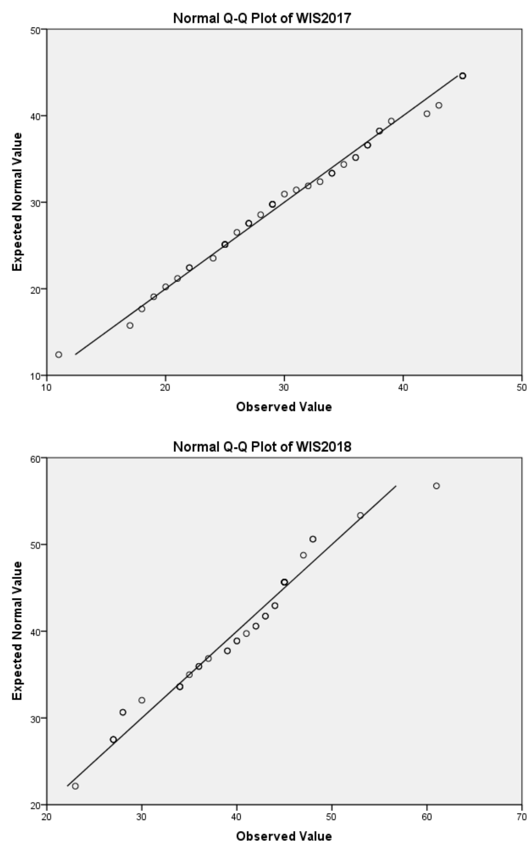

FIGURE 1
Q-Q PLOTS OF WIS2017 AND WIS2018

Table 4 depicted the percentage of students that showed gains from 2017 to 2018. The percentages listed in the ascending order were INF (63.9%), SKILL (69.4%), ATT (72.2%), PG (75.0%), and WIS (83.3%) respectively. Data showed that most students had increased their gains in the above five dimensions.

TABLE 4
PERCENTAGE OF STUDENTS THAT SHOWED GAINS FROM 2017 TO 2018

	WIS	PG	SKILL	ATT	INF
% of students that showed gains	83.3%	75.0%	69.4%	72.2%	63.9%

Paired sample t-tests were conducted to determine whether there were significant differences from each student's responses to WIS, PG, SKILL, ATT, and INF between 2017 and 2018 (see Table 5). The positive mean values demonstrated improvement in learning outcomes in 2018 compared to 2017. Significant differences between students' responses from 2017 to 2018 are found for WIS, PG, SKILL, ATT, and INF. These results demonstrate student improvement in areas such as their understanding of the nature of science, research skills, confidence as both independent and collaborative researchers, feeling part of a scientific community, and their likelihood of pursuing advanced degrees in STEM fields.

TABLE 5
PAIRED SAMPLE T-TESTS OF INDEPENDENT VARIABLES

	Paired Differences		t	df	p-value
	Mean	Std. Deviation			
WIS2018 - WIS2017	9.272	13.48	4.563	35	0
PG2018 - PG2017	7.818	15.23	3.404	35	0.001
SKILL2018 - SKILL2017	12.818	23.01	3.694	35	0.001
ATT2018 - ATT2017	8.431	16.37	3.415	35	0.001
INF2018 - INF2017	4.295	9.07	3.14	35	0.003

A Mann-Whitney U test was used to test for significant differences between juniors and seniors within each year. In 2017, we tested for differences between 20 juniors and 8 seniors. We find that all five variables showed non-significant results and thus we could not reject $\mathrm{H}_0: \mu_j = \mu_s$. However, we do note that seniors reported higher gains than juniors across all five variables (indicated by negative Z values).

TABLE 6
MANN WHITNEY U TEST BETWEEN JUNIORS AND SENIORS IN 2017

	WIS 2017	PG 2017	SKILL 2017	ATT 2017	INF 2017
Mann-Whitney U	67.5	68	75	56.5	56.5
Wilcoxon W	277.5	278	285	266.5	266.5
Z	-0.636	-0.612	-0.255	-1.2	-1.206
p-value	.533	.566	.823	.237	.237

In 2018, we tested for differences between 16 juniors and 20 seniors. We find that all five variables showed non-significant results and thus we could not reject $H_0: \mu_j = \mu_s$. As in 2017, we note that seniors reported higher gains than juniors across all five variables (indicated by negative Z values).

TABLE 7
MANN WHITNEY U TEST BETWEEN JUNIORS AND SENIORS IN 2018

	WIS 2018	PG 2018	SKILL 2018	ATT 2018	INF 2018
Mann-Whitney U	117.0	119.5	127.5	111.5	136.0
Wilcoxon W	253.0	255.5	263.5	247.5	272.0
Z	-1.375	-1.297	-1.036	-1.550	-.771
p-value	.178	.200	.305	.124	.459

DISCUSSION

Students in the PRISMS research program complete a two-year, on-campus research project in a discipline of their choosing. Here, we present survey results from a cohort of 44 students in the program. These results indicate significant gains across all five categories of learning outcomes measured. Students in the PRISMS program self-report gains in research skills, increased aspiration to STEM majors and careers, improved ability to think and work like a scientist, increased scientific self-efficacy, and feeling like a part of a scientific community. These findings are broadly consistent with the learning outcomes reported in other studies of secondary school STEM research experiences [1], [5], [14].

A growing body of literature discusses the variety of models for secondary school research programs. These models range from 1-2 week summer extracurricular programs to extended (> 6 months) programs where all research is conducted at the student's school [1], [5], [15], [16]. Establishing the benefits of these programs and assessing how the features of different models contribute to student outcomes and experiences has been identified as an area in critical need of empirical attention [5]. The diversity of secondary school research programs makes it difficult to systematically categorize them into different models, however it is clear that one key dimension is the degree to which the program is integrated into a school's curriculum [17].

The PRISMS research program represents a model in which the program is fully integrated into the school's curriculum. Two key factors are responsible for integration: all mentors and labs are internal to PRISMS and two years of research is a required part of the curriculum. The program is also integrated into the curriculum in the sense that we have research labs in all core STEM disciplines; students can progress from taking introductory classes and AP classes to pursuing a research project in that discipline. Students also have the freedom to develop an integrated project that spans multiple disciplines. Despite the diversity of disciplines, mentors, and projects, the results presented here indicate that students generally feel positively about their research experience (gains in ATT and INF). Although there is some level of current success, the PRISMS research program has evolved considerably since its inception and many lessons have been learned along the way. In the following sections, we discuss some of the unique advantages, challenges, and opportunities associated with this integrated model of a secondary school research program with particular attention to the role of internal mentors, the length of the research experience, and the relationship to school culture.

INTERNAL MENTORS AND LABS

The quality of the mentor-student relationship has been identified as a key variable influencing the learning outcomes of a research experience [1], [4], [8]–[10]. A consequence of having internal mentors and labs is the familiarity of students and mentors. At PRISMS, students typically already have a relationship with the mentor because they have taken a class with them or participated in an extracurricular activity led by the faculty member. This should be highly conducive to the development of a quality mentor-student relationship where the mentor knows the student's personality and has a strong sense of their skills and knowledge. Even in the case where there is no prior familiarity, the mentor will likely have more experience working with high school students than would be typical for a university-based programs.

Another major advantage of having internal labs and mentors is that it facilitates collaboration and the development of interdisciplinary projects. It is not uncommon at PRISMS for students to spend significant time consulting with other mentors or using equipment in their labs. In some cases, the project evolves to the point where it makes sense for a student to change labs half-way through the two-year research period. For more extended discussion on the way in which the PRISMS model allows for authentic integration of numerous disciplines see [11].

Aside from the obvious practical challenges of funding and operating research-capable labs, a major challenge of the PRISMS model is the significant responsibility it places on research mentors. We also commonly refer to mentors as research directors as this perhaps better describes the role. Research directors must work with multiple students to develop pedagogically meaningful projects, supervise students as they conduct the research, and manage all equipment and materials in their lab. While not essential, prior experience in research is certainly beneficial; the majority of research directors at PRISMS have post-undergraduate research experience in their discipline. This model also places a premium on limiting turnover amongst faculty. It can be difficult to take over a lab previously managed by someone else and it simply takes time to develop promising directions for research.

Though it requires significant effort and time on the part of the research directors and the school in general, there are numerous ancillary benefits to having teachers actively participate in research [1], [18]–[20]. In our experience, the freedom research mentors have to develop projects can be motivating and fun. Experiments conducted as a part of a student's project can be adapted for inquiry-based labs and lessons. Conducting research also helps teachers focus on the skills needed to be a successful researcher and can provide the impetus for finding ways to better teach these skills in their classes.

LENGTH OF THE RESEARCH EXPERIENCE

The two-year length of the PRISMS research program also offers significant advantages and challenges. In the best-case scenario, the length of the program allows for a truly authentic experience in which a student goes through multiple iterations of the scientific method and builds a variety of skills throughout the project. However, maintaining a high school student's interest and engagement over such a long period of time can be difficult. Studies that have found limited or no learning gains from secondary school research experiences highlight the time-consuming and tedious nature of data collection and a lack of epistemic involvement in generating research questions or data analysis [21]–[23]. Avoiding tedium and creating a pedagogically meaningful experience over the course of two years can be a considerable challenge for PRISMS research mentors.

Evidence indicates that the length of a research experience has a positive relationship with learning gains [1], [12], [24]. Small sample sizes limit our ability to detect differences in learning outcomes between juniors (one year) and seniors (two years) in the PRISMS program; although all comparisons were non-significant, we do find that seniors in both 2017 and 2018 report higher learning gains across all five variables measured. Further work is needed to assess whether the two years of research offers substantial benefits over shorter time frames.

INTEGRATION OF RESEARCH PROGRAM INTO SCHOOL CULTURE

An integrated research program provides a unique opportunity to influence the culture and values of a school community. At PRISMS, we find that our research program has enabled a distinct culture to emerge where inquiry and innovation are highly valued. Interestingly, we observe that this "culture of research" initiates a positive feedback loop that enhances the pedagogical effectiveness of the research program — research is valued and celebrated; students are interested and motivated to participate in research and thus are more likely to have a meaningful learning experience; students value research more highly because of their positive experience, and so on. The culture of research likely shapes the attitudes and self-efficacy of all students to some degree, but it may be particularly valuable for students from groups typically underrepresented in STEM. Over the last few years, numerous activities and practices have developed that we believe enhance the positive culture surrounding research and thereby influence the learning outcomes of our program.

The "Research Day" is a major event which sets the culture of PRISMS. This is an important experience for underclassmen; before their entry into the research program, a student has attended four research days where they have listened to their peers and asked them questions about their projects. Another school-wide event of importance is the "morning meeting" — a 10-minute gathering in which announcements are made. Events such as conferences, science fairs, and research competitions are announced, and any awards won at these events are celebrated. The awarding of Nobel Prizes and other scientific news (such as the recent birth of the first genetically modified humans) are briefly discussed by faculty or the headmaster. The headmaster also frequently does a "this day in history" where major scientific and technological breakthroughs and their impact on human history are considered. On Fridays, seniors give a 2-3-minute presentation about their research to the entire school; in addition to Research Day, this is the other formal way in which students learn about the work of their classmates.

Efforts are also made to keep the attitude around research light and fun which we believe has benefits for student interest in research and career aspirations. It is not uncommon to have holiday parties for research students or have impromptu trips off campus for ice cream. In 2018, another fun tradition started regarding the placement of sophomores into their research lab for the following year - a school-wide "sorting hat" ceremony based on Harry Potter. Students sit on a chair (with a hidden speaker underneath) and have a wizard's hat placed on their head. A whimsical speech is given about the student's interests and abilities and their lab placement is announced with much fanfare and applause from the student body.

PRISMS is certainly not the only STEM high school with a culture where inquiry and innovation are valued [25]–[28], however this culture may be strengthened by several factors unique to PRISMS . The small size (82 students) and nature of the student population (approximately 75% of the students live in on-campus dorms) allow for a more cohesive culture to form than might otherwise be possible. In addition, many of the Chinese students come from a gifted and talented program in Beijing and thus already have familiarity with each other and a strong interest in STEM disciplines before they get to PRISMS. Although the specific features and practices of PRISMS may be particularly conducive to developing a cohesive research culture, we believe that it is possible and essential for all schools with research programs to promote positive attitudes towards research.

Conclusion and Future Directions

The PRISMS research program requires students to complete a two-year project in a STEM discipline of their choosing with mentors and labs internal to the school. Students in the program took the URSSA survey following the 2016-2017 and 2017-2018 school years; learning outcomes were assessed using a paired t-test for individual students in the research program for both years. The results indicate statistically significant gains in the 5 variables measured — (1) gains in thinking and working like a scientist (WIS); (2) personal gains related to research work (PG); (3) gains in skills (SKILL); (4) attitudes or behaviors as a researcher (ATT), and (5) career and graduate education aspirations (INF). In addition, we test for differences in learning outcomes between juniors (one year in the program) and seniors (two years) using a Mann-Whitney U test and find that there are no statistically significant differences. The positive learning outcomes of the PRISMS program suggest that integrated school-based STEM research programs represent a viable model for engaging secondary students in authentic research experiences.

This study also suggests several promising directions for future research. One limitation of this study is that the URSSA survey is aimed at undergraduate research experiences; many of the questions were not particularly relevant to students in our program. This points to a need for assessment models and relevant evaluation scales for high school research programs. Future work might investigate how and to what extent the specific aspects of the research experience, such as the length of the research program, the autonomy given to mentors and students, and the integration of the program into the school's curriculum and culture affect learning outcomes. Questions that should be addressed with targeted research include: Do longer research experiences for high school students (> 1 year) offer substantial benefits over shorter time frames? Do students in school-based research programs with internal mentors typically have more pedagogically meaningful relationships with their mentors compared to students in external research programs? How do integrated research programs influence school culture and vice versa?

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