

Teaching the Genome Generation: Engaging High School Students in Authentic Human Genetics Investigations

Sarah Wojiski¹, Christina Vallianatos¹, Kristin M. Bass², Erica L. Gerace^{1,3}, Alexa Wnorowski¹, and Charles Wray¹

¹Department of Genomic Education, The Jackson Laboratory, Bar Harbor, ME and Farmington, CT; ²Rockman et al Cooperative, Berkeley, CA; and ³Department of Genetics, Yale School of Medicine, New Haven, CT.

Keywords: High School Research Program, Mentorship, STEM Outreach, STEM Careers, College Preparation, Broadening Participation, Underrepresented Youth

Publication Date: June 29, 2026

DOI: <https://doi.org/10.15695/jstem/v9i1.01>

ABSTRACT: Teaching the Genome Generation™ (TtGG) provides high school teachers with the content knowledge, teaching strategies, and resources needed to enhance student learning in genetics and genomics. Our approach integrates three curricular strands—human molecular genetics labs, bioinformatics activities, and bioethics lessons—to provide students with authentic science investigation experiences. Students examine genotypes and phenotypes associated with athletic performance and other relatable situations, enabling them to connect abstract biological concepts to their everyday lives. To assess the impact of our program on the knowledge, skills, and attitudes that students need to persist in STEM, we conducted an exploratory classroom study with 12 high school biology teachers and 344 students, with an emphasis on the molecular genetics laboratory component of the program. Key findings indicate that our curriculum leads to increased knowledge of and confidence in biotechnology laboratory procedures. Students felt that they were conducting experiments that were similar to what “real” scientists do and had an increased interest in careers related to biomedical science. We consider how efficient, adaptable lab protocols like ours can make the most of teachers’ limited class time. We also provide recommendations for designing precise studies and instruments to evaluate knowledge outcomes.

INTRODUCTION

Science, Technology, Engineering, and Mathematics (STEM) education has been deemed a national priority, essential for fostering an innovative workforce that can contribute to the rapid technological advances occurring across the globe (National Science Foundation [NSF], 2007; U.S. Department of Education [ED], 2015). Yet, attrition from STEM fields as students progress through their education, also described as a lack of STEM persistence, continues to be a barrier to realizing this goal (ED, 2015; President’s Council of Advisors on Science and Technology [PCAST], 2012). Numerous studies have examined the factors contributing to STEM persistence, offering opportunities for educational reform and curricular innovations that can mitigate the continued exodus from STEM disciplines (Chang et al., 2014; Cooper et al., 2019; Estrada et al., 2017; Gandhi-Lee

et al., 2017; Graham et al., 2013; Maltese & Tai, 2011). An analysis of school-based factors that lead to persistence in STEM majors among undergraduates indicates that most students make their decision to pursue a STEM pathway while in high school (Maltese & Tai, 2011). Thus, interventions at the high school level may be more effective in encouraging students to stay and persist in STEM disciplines in college.

One promising intervention, described in Graham et al.’s (2013) “persistence framework,” exposes students to content that is relevant to their lives. This approach allows students to build new knowledge on prior learning and experiences, while illuminating ways that science directly impacts humans and society. It also provides opportunities for students to explore potential career paths in STEM and “see themselves” as scientists.

Genetics stands out as a scientific area that is rapidly permeating modern society. We are in the era of direct-to-consumer genetic testing (for both humans and pets), genetically modified organisms, and gene editing, where genetics is having a direct impact on healthcare, our environment, and our identities. Given that many students' only exposure to genetics will be in their high school biology classroom, building genetics literacy in high school is critical to the development of informed future healthcare consumers and citizens (Chapman et al., 2019; Stern & Kampourakis, 2017). Therefore, there is a need to reform standard high school genetics curricula which often tend to focus on traditional and historical concepts, including pea plant crosses and Punnett squares (Smith, 2014a; Smith, 2014b; Stern & Kampourakis, 2017). Thus, in the biology classroom, there is ample opportunity to modernize the curriculum, making it more relevant to students' lives and connecting content to personal experience. This could lead to deeper student engagement with the content, enhanced student learning, and ultimately greater interest and persistence in future STEM studies.

Given the extent to which genetic and genomic testing is becoming a part of routine health care, it is not surprising that initial efforts to incorporate personal genetic testing in the classroom occurred in health professions curricula. As reviewed in Garber et al. (2016), most of these interventions have involved the voluntary use of direct-to-consumer genetic testing in the medical or graduate school classroom. Studies have indicated that undergoing personal genetic testing as part of coursework increased healthcare professional students' confidence in their ability to explain and interpret test results to future patients and gave students a deeper appreciation of the role of genetic and genomic testing in the healthcare setting (Ormond et al., 2011; Sanderson et al., 2013; Vernez et al., 2013). It also led to a greater interest in studying these topics further. While pre/post knowledge tests and assessments revealed some knowledge gains, these gains were often minimal and statistical significance varied (Salari et al., 2013; Sanderson et al., 2013).

Personal genomics data analysis has also been utilized in the undergraduate classroom, with data indicating that these experiences enhance student engagement and motivation but often do not result in significant learning gains. In a study by Weber et al. (2015), students were offered the opportunity to receive a personal genomics testing kit after the completion of an advanced molecular biology or genomics course. Anticipation of receiving the testing kit and undergoing the testing were enough to enhance student interest and the classroom learning environment, based upon time invested researching personal genetic material and self-reported attitudes. Students receiving the testing kits also expressed greater confidence in the value of classroom discussions and assignments and spent more time out of class studying the topics. Howev-

er, students who would be receiving the kits did not demonstrate statistically significant knowledge gains compared to students who did not receive kits. Research on the use of personal microbiome testing in undergraduate immunology, advanced molecular biology, or genomics courses yielded similar results (Weber et al., 2018). Personal microbiome analysis significantly enhanced student engagement and interest as assessed through self-reported time spent on assignments, enjoyment of course content, and attitudes about the courses. In contrast, quiz results on knowledge questions did not improve between those students undergoing testing and those not receiving the personal microbiome test.

Whitley et al. (2020) reviewed the introduction of personal genomics topics at the high school, undergraduate, and medical education levels. The authors suggest that in high school, personal genomics lessons should serve three goals: (1) to introduce students to modern topics in human genetics, (2) to increase students' interest in genetics, and (3) to inspire students to consider potential STEM majors. Inclusion of personal genomics and its relevance to human health and society is of critical importance, given that many high school textbooks do not include discussion of non-Mendelian inheritance, multifactorial diseases, and complex traits (Hicks et al., 2014).

The past decade has seen an increase in studies describing the incorporation of modern genomics topics into high school classrooms, including those employing publicly available bioinformatics databases and tools, such as NCBI (National Library of Medicine, n.d.b) and BLAST (National Library of Medicine, n.d.a). Martins et al. (2018) used an inquiry-based approach to motivate students to examine genomic sequences and genomic information to identify probable genes and their evolutionary relationships across species. Dedhia et al. (2019) prepared tutorial exercises for high school students to learn how to use the Gene Ontology system and its analysis tools. Student surveys indicated that students found the lessons enjoyable and that they learned something new that could be applied to future database use.

In a study of high school curricula focused on health and medical applications of biotechnology with students in Western Australia, knowledge and attitude assessments measured whether direct teaching of these concepts can shift preconceived misconceptions or attitudes that students may have about biotechnology applications (van Lieshout & Dawson, 2016). Results from pretests and posttests indicated that a single lesson on this topic can increase the ability of students to identify biotechnology applications relevant to human health and that student attitudes toward biotechnology were generally favorable and did not shift considerably after instruction on the topic.

Other studies have incorporated participatory genetics, whereby high school students have provided their own DNA samples for analysis as part of the learning experience. Atha-

nasiadis et al. (2016) describe a study conducted in Denmark whereby over 600 high school students provided saliva samples for genotyping and completed a questionnaire regarding family members' places of birth and basic anthropometric traits to assist in mapping the genetic history of the Danish population. The students also participated in two symposia to learn about human genomics, human evolution, and genotyping technologies. The students then received aggregated testing results. Perceived engagement and extensive media coverage and publicity during the symposia illustrated the project's success, though measures of student learning gains or attitudes about human genomics were not collected. Yang et al. (2017) engaged high school students in an examination of the concept of race through next-generation sequencing of their own DNA samples, and analysis of their genetic similarity to their classmates. Through pre- and post-tests, the authors reported significant learning gains around sequencing technology and bioinformatics. Attitude surveys indicated positive shifts in students' perceived self-efficacy and skill in genetics.

Cumulatively, these studies indicate that timely introduction of modern genetics and genomics curriculum with clear connections to students' personal lives can impact student knowledge gains and attitudes. With the goal of illuminating the relevance of genetics to everyday lives and celebrating human genetic diversity, The Jackson Laboratory (JAX) has developed *Teaching the Genome Generation*TM (TtGG), a high school teacher professional development program and curriculum resource (LaRue et al., 2018). TtGG brings modern genetics and genomics topics into the high school classroom through the integration of three curricular strands:

- molecular genetics laboratory protocols
- bioinformatics exercises that introduce genomic databases, data analysis, and data interpretation
- bioethics lessons that examine the societal, legal, and ethical implications of genetic testing and genetics research

This paper describes evaluation of the TtGG laboratory activities through a classroom study of 12 high school teachers and 344 students. The study described herein provides evidence of the feasibility and effectiveness of our laboratory curriculum, documenting TtGG's effect on the knowledge, skills, and attitudes students need to persist in STEM. Our study design evaluated teachers' use of the curriculum during the two-week window when they had access to our mobile laboratory kit resources since this is when teachers use the TtGG curriculum most consistently, thus providing greater fidelity of assessment of our program. As such, the data captured during that two-week period is reflective of the teachers' implementation of the laboratory curriculum only; we were unable to assess the impact of bioinformatics and

bioethics lessons taught outside of the two-week window. A second classroom study that is nearing completion examines the effectiveness of our bioinformatics lessons in a consistent, time-bound manner, thereby increasing fidelity of bioinformatics content delivery during classroom implementation. Incorporating lessons learned through this classroom study, this paper also previews the next iterations of TtGG programming and offers suggestions for those doing similar curriculum evaluations in a classroom setting.

METHODS

Program Description. The TtGG program's professional development (PD) training for high school teachers and its impact on teacher efficacy in the classroom has been described previously (LaRue et al., 2018). Herein, we focus on the student-facing laboratory elements of the program. TtGG celebrates human genetic variation by bringing human DNA variants and phenotypes into the classroom for laboratory investigation and discovery. The end goal of the molecular lab experience is to determine the genotypes present in anonymized DNA samples, providing opportunity to build genetics and bioethics knowledge as well as develop molecular and computational skills along the way.

The TtGG molecular labs are crafted around phenotypes that are relatable—and therefore approachable—to youth regardless of cultural background or academic experience. To capture students' interest, five genes are part of the TtGG curriculum, each associated with a different phenotype. In relation to athletics, students may wonder why athletes often choose either power or endurance sports, but rarely both. Through TtGG, students examine variations in two genes, angiotensin I converting enzyme (*ACE*) and actinin alpha 3 (*ACTN3*), to discover examples of genetic variants that contribute to athletic performance. Exploring variants in cytochrome P450 family 2 subfamily C member 19 (*CYP2C19*) shows students how genetic differences can affect how the liver metabolizes a range of compounds, from medications to caffeine. The “love” gene oxytocin receptor (*OXTR*) plays a role in human emotions and social behaviors like coping with stress, and *OXTR* variants potentially affect these phenotypes. Variants in taste 2 receptor member 38 (*TAS2R38*) can contribute to a wide variety of bitter tasting phenotypes, such as those detected with the PTC paper commonly used in K-12 genetics lessons. Our curriculum includes an informational “gene sheet” for each TtGG gene that further describes the variants being assessed and the phenotypic correlations observed in human populations (see sample gene sheet in Appendix, Figure A1). Importantly, the gene sheets also reinforce that association does not mean causation, and that many factors (genetic and non-genetic) contribute to the observed phenotypes.

The TtGG molecular labs start by using human DNAs, where anonymous samples are provided by the students or by JAX to explore genetic variation in the classroom population. The JAX Institutional Review Board (IRB) determined that laboratory activities used by high school students are not generalizable research or human subjects research for the following reasons: the program uses a strict laboratory protocol that makes all the human saliva/DNA samples anonymous; no genetic data is collected, shared, or saved after the laboratory demonstration; and all samples used in the demonstration laboratory exercises are discarded after the labs are completed. To educate all those involved and foster best practice, JAX leads a session on informed consent during the TtGG PD course for teachers, in which educators are trained to discuss with their students issues around genetic data privacy and when consent and assent are needed. Additionally, for use at each teacher's discretion and approved by the JAX IRB, TtGG provides a passive consent form that teachers can send home with students. This consent form alerts parents/guardians to the TtGG demonstration of molecular genetic assays of anonymized student DNA that will be used in high school labs. Parents can opt their students out of participation and students themselves can opt-out (non-assent to participate) of any DNA collection and purification protocols. Importantly, all DNA samples—whether provided by the students or by JAX—are anonymized and redistributed to the class by the teacher so that samples cannot be traced to any individual.

Five protocols—four molecular genetics labs and one bioinformatic assay—are available in the TtGG curriculum (Figure 1); students experience at least three assays (DNA extraction, polymerase chain reaction [PCR], and gel electrophoresis) to determine the genotypes of their samples. Depending on the gene chosen, the pathway for genotyping

analysis will vary. Because the variant of interest in the *ACE* gene is a 287 base pair [bp] insertion/deletion, the genotypes of *ACE* samples can be determined by size differences of PCR fragments resolved using gel electrophoresis. For more extensive analysis, teachers may choose to conduct genotyping assays on either the *CYP2C19* or *OXTR* genes which require restriction enzyme digest to aid in genotype determination after gel electrophoresis. These three gene assays are purely lab-based. Exploring *ACTN3*, *CYP2C19*, or *TAS2R38* gene variants allows students to add bioinformatics skills through variant detection via Sanger sequencing analysis. Teachers can choose multiple genes to assay, which reinforces the concept that each gene differs in structure (sequence, genotype) and function (phenotype).

Each protocol includes a detailed written step-by-step guide and accompanying video demonstration, providing complete laboratory instructions for both students and teachers (see Appendix, Figure A2). The entire lab setup, including equipment, reagents, and consumables, is loaned to New England-area teachers for two weeks at no cost to them. These TtGG lab “kits” are packaged in-house by the TtGG team, with high-grade, professional scientific equipment to ensure students receive an authentic laboratory experience.

The lab portion of the TtGG curriculum ends with interpreting genotypes for the class population, examining the spectrum of genetic variation that exists within the population, and using genotypes to then infer what phenotype is expected based on the gene assay. TtGG training cautions teachers and students against ideas of genetic determinism, where genotypes dictate phenotypes in absoluteness, and instead encourages discussion around the complexities of the human genome and the influence of variants in a myriad of other genes as well as the environment.

While our classroom study focused on the molecular genetics laboratory assays, the TtGG curriculum extends beyond the lab bench, affording students the opportunity to gain skills in two additional areas important in genetics: bioinformatics and bioethics (Figure 2). Bioinformatics exercises introduce computational topics, either as extensions from the lab or stand-alone lessons. Some gene assays lead students to discovering genotypes via Sanger sequence analysis, as introduced above. Students use free sequence analysis software to view real human sequence files, assess quality, search sequences for the TtGG variant of interest, and call genotypes. Additional lessons teach publicly available genomic database and sequence alignment tools such as OMIM (Johns Hopkins University, n.d.), BLAST (National Library of Medicine, n.d.a), and Ensembl (Dyer et al., 2025). Bioethics conversations and exercises can be woven throughout every lab or computational lesson to integrate ethical and social considerations. Through collaboration with Personal Genetics Education & Dialogue (PGED; Harvard Medical School, n.d.), real case studies from history or today's news

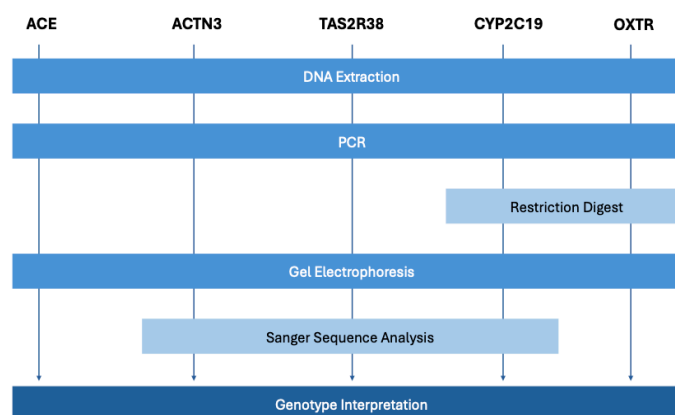


Figure 1. The five TtGG genes (top) and the laboratory protocol steps needed to assay each gene to determine and interpret genotypes. Arrows running through a protocol step indicate which laboratory skill is used in which gene assay. ACE = angiotensin I converting enzyme; ACTN3 = actinin alpha 3; TAS2R38 = taste 2 receptor member 38; CYP2C19 = cytochrome P450 family 2 subfamily C member 19; OXTR = oxytocin receptor.

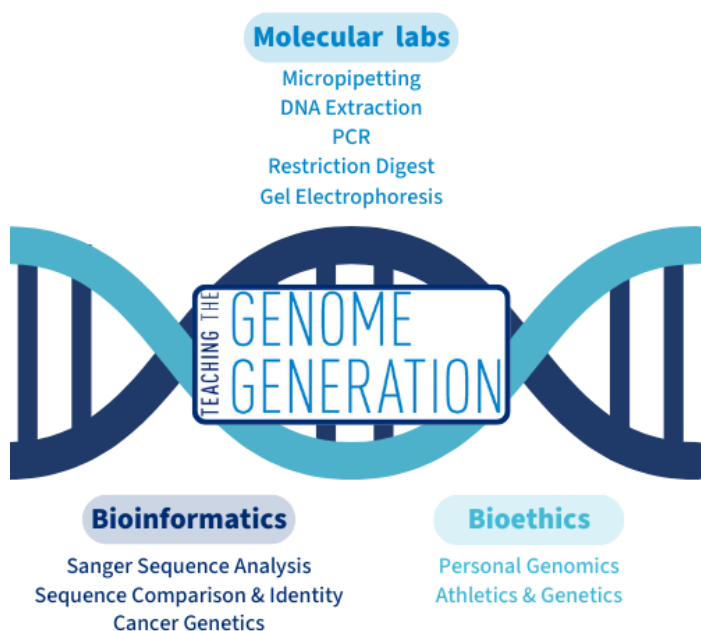


Figure 2. The TtGG program builds skills in personalized genetics and genomics by weaving together molecular labs, bioinformatics exercises, and bioethics discussions.

are presented to students to emphasize how classroom learnings extend to real life issues. PGED has been a collaborative partner of TtGG since the program's inception. PGED staff attend our summer teacher PD and lead sessions on topics such as Genetics and Athletics (which aligns with our genetic variants in the *ACE* and *ACTN3* genes), Eugenics, and Ancestry and Identity. PGED staff have also advised the TtGG team on our informed consent discussions with teachers and the ethics content that TtGG staff have developed and integrated into new lessons on genomic data analysis. During PD, teachers are provided with sample curriculum maps that demonstrate how the labs, bioinformatic lessons, and bioethics activities can be integrated (see Appendix, Figure A3). Unlike the laboratory kits and reagents sent to schools for two weeks at a time, the bioinformatics and bioethics lessons are open access and freely available online; thus, teachers can use these resources at their own pace at any time throughout the school year—not just during the two-week period that they are using the TtGG lab kits. The non-laboratory elements of the curriculum have been evaluated separately and will be the subject of a second classroom study that will be reported in a future manuscript.

The TtGG program seeks to expose students to “real” science, carrying out laboratory investigations just as a geneticist would—examining human DNA, using advanced equipment, and discovering unknown genotypes in a population of individuals—with the goal of increasing interest in science and understanding how science (and specifically genetics) is important in our everyday lives. Through a classroom study, we sought to examine the impact of the TtGG laboratory curriculum on students' content knowledge, attitudes, and

opinions about genetics and genomics.

Evaluation Methods. We used the following methods in carrying out this study.

Questions and Design. Our evaluation of the TtGG materials' effectiveness explored two questions:

1. Primary. What is the impact of the TtGG curriculum on students' (a) knowledge of genetics and genomics content, lab procedures, bioethics, and bioinformatics; (b) confidence engaging in genomics concepts and lab activities; and (c) interest in engaging in additional genomics-related behavior, including academic and career pursuits?
2. Secondary. Do students taught by experienced TtGG teachers who have taught the curriculum at least three times change more than those with a novice TtGG teacher using the curriculum for the first or second time?

Since this was the first comprehensive classroom study of the TtGG lessons, we used a treatment-only pre-post design to assess their “promise of generating the intended outcomes” (Institute of Education Sciences, 2013, p. 47). We also recognized that because TtGG provides teachers with high-grade professional scientific equipment and a corresponding approach to teaching genetics, there was not a suitable “business-as-usual” condition. We were more interested in exploring the impact of the TtGG curriculum materials on student learning.

We anticipated that “TtGG experienced” teachers (which we defined as those who had taught the TtGG curriculum at least three times prior) would be better able to implement the lab protocols more efficiently, and integrate the bioinformatics and bioethics content into their teaching, compared to “TtGG novice” teachers (those who were teaching the TtGG curriculum for the first or second time). This would, in turn, lead to greater gains in student knowledge and science attitudes.

Participants. We recruited high school teachers who had taken our TtGG professional development short course and who were teaching introductory biology. A total of 13 teachers participated, nine teachers who were experienced with the TtGG curriculum and four who were novices. The novice teachers were not new to teaching but were simply new to the TtGG program. The TtGG novice teachers had 3-34 years (median = 11) of teaching experience while the experienced teachers had 13-40 years (median = 20).

After collecting the data, we dropped one teacher and 22 students from the study because of the distribution of their prescores and postscores. That classroom's mean pre-post

Table 1. Representative questions from TtGG Student Knowledge Survey. The correct answers are bolded.

Concept	Number of Items	Sample Items
Molecular Genetics	10	Genetic variants are defined as the: - result of genetic disease differences between individuals' DNA sequences - four different nucleotides or bases (A, G, C, T) that make up DNA - differences between the DNA sequences of different genes from the same individual
Molecular Genetics Lab Procedures	3	In performing a genetic analysis, why must the DNA fragments of interest be copied using the Polymerase Chain Reaction? To make enough DNA to be analyzed - To sequence one single strand of DNA - To collect DNA from the individual - To provide a negative control in the experiment
Bioethics	3	A college sports recruiter is asking an incoming college athlete to participate in a genetic test which would reveal a variation in the ACE gene associated with improved endurance performance. The test results will be beneficial to the recruiter and athlete because: - The result of the test will inform the coach and student that the student will become an elite endurance athlete. - The result of the test will inform the coach and student that the student will become an elite endurance athlete with athletic training and a healthy lifestyle. The result of the test will inform the coach and student of the genotype of a single gene that is associated with improved endurance. - The result of the test will inform the coach and student of the complete biological effect of the ACE genotype.
Bioinformatics	3	An online genome database can be used to: - sequence an individual genome select, align, and compare gene sequences - identify your risk for cancer - detect genetic diseases

change for the knowledge assessment (total score) was substantially lower (-2.89 Z scores) than the means for all the other teachers. The final analytic sample was 12 teachers (eight experienced, four novice) and 344 students.

Most students were white (81.2%) and did not identify as Hispanic or Latino (74.4%). There was about equal representation of female and male-identifying students (43.3% and 44.8%, respectively). Demographic details for student gender, race, and ethnicity are shown in the Appendix, Figure A4. We did not collect demographic data on the participating teachers.

IRB Approval. We received human subjects approval from The Jackson Laboratory's Institutional Review Board (Number 2020-068) for the survey data collection. Parents and guardians consented passively for their students to participate in the classroom study and the students provided active assent. Teachers consented in their online surveys.

Measures. We used one student and two teacher measures in our study.

Student Surveys. The TtGG staff, in consultation with Rockman et al. evaluators, developed identical presurveys and postsurveys to assess students' knowledge of molecular ge-

netics, bioinformatics, and bioethics content and methods, as well as attitudes toward science (see Tables 1 and 2 for representative survey questions). The 19 content questions measured students' understanding of: (a) molecular genetics content, (b) lab procedures, (c) bioethics, and (d) bioinformatics (use of online databases to examine gene sequences and other genetic information). Nine of the 10 molecular genetics content questions came from two published instruments: the Genetics Literacy Assessment for Secondary Schools (GLASS; Keyes, 2019), and the GKKnowM genomics knowledge scale (Linderman et al., 2021). The GLASS items had been validated with high school students. The TtGG team decided that while the GKKnowM instrument had been validated with adults, the content and wording of the items they selected were appropriate for their curriculum.

TtGG staff created one additional molecular genetics content item and three items each about lab procedures, bioethics, and bioinformatics. Evaluators reviewed these items against recommended best practices for multiple choice questions (Bass et al., 2016; Haladyna et al., 2002). This served as content evidence for their validity (Reeves & Marbach-Ad, 2016).

The attitude survey (Table 2) contained 19 items about students' confidence and interest in genetics and genomics-related activities. The confidence items followed Bandu-

Table 2. Representative questions from the TtGG Student Attitude Survey.

Construct	Number of Items	Sample Items
Interest in genetics and genomics activities	7	How interested are you in doing the following things before you graduate from high school? - Watching a YouTube video about genetics - Talking to a health professional (e.g., nurse, doctor) about genetics or genetic testing <u>Response scale:</u> 1 = Not at all likely, 4 = Somewhat likely, 7 = Very likely
Self-efficacy for genetics-related tasks	12	Please rate how confident you are that you can perform the following tasks: - Accurately measure samples with a micropipette. - Correctly explain how a genotype can be determined using laboratory procedures. - List at least two ways in which personal genetics might impact your life. <u>Response scale:</u> 0 = I've never done this before, 1 = I've tried but I cannot do this at all, 4 = I am moderately certain I can do this, 7 = I am highly certain I can do this
Scientific authenticity of TtGG materials	1	{Pre} Think about the biology labs you do in class. How similar are they to the work that scientists do in their own labs? {Post} Think about the genetics labs you just did in class. How similar were they to the work that scientists do in their own labs? 1 = My labs are very similar to what scientists do. 2 = My labs are similar to what scientists do. 3 = My labs are a little similar to what scientists do. 4 = My labs are a little different from what scientists do. 5 = My labs are different from what scientists do. 6 = My labs are very different from what scientists do. Please explain your answer.
General reactions to TtGG materials	4	- How would you describe the genetics and genomics lessons you did to a student who will be taking this course next year? - Two things I learned as a result of these lessons... - Two things I didn't entirely expect, but am pleased to have gained from these lessons... - Two things I would like to study or do more from these lessons ...

ra's (2006) guidelines for creating self-efficacy measures by identifying specific conceptual and procedural tasks that students should be able to do more proficiently after the TtGG lessons. Students rated their confidence for those tasks on a seven-point Likert scale; they also could indicate if they had never done an activity and therefore had no means to judge their ability. TtGG staff also identified eight genetics-related activities that students might want to do before they graduated from high school. Students rated their interest in those activities on a seven-point Likert scale.

The surveys also elicited students' reactions to the TtGG materials. On the presurveys and postsurveys, students rated the similarity of their classroom lab activities to what scientists do in their own labs (Michael et al., 2021). We expected that students would recognize the authenticity of the TtGG lab protocols and professional-grade equipment. The post survey contained additional open-ended questions asking students to describe the course to a peer and reflect on what they had learned and would want to learn in the future. The reflection questions came from the earlier evaluation of the TtGG teacher professional development short course (LaRue et al., 2018).

Teacher Surveys.

Lesson Logs. Teachers completed an online instruction-

al log to describe how they implemented each lesson. Questions included: (a) the level of emphasis placed on TtGG topics; (b) the connections made between molecular genetics, bioinformatics, and bioethics; (c) students' level of engagement compared to non-TtGG lessons; and (d) students' key takeaways from the lessons.

Post-Implementation Survey. Teachers completed another survey at the end of the school year about their overall experience with the TtGG program (LaRue et al., 2018). Questions relevant to the classroom study included teachers' goals for the unit, what students took away from the materials, and the extent to which teachers had covered bioethics and bioinformatics (and why).

Data Analysis. Our mixed-methods study design included both quantitative and qualitative data.

Quantitative Data. We conducted parametric and nonparametric analyses, depending on the nature of the data. In all cases, we reported test statistics, *p* values, and effect sizes. We scored the knowledge items and summed them as a whole and for each subscale (molecular genetics, lab procedures). We then conducted paired-samples *t* tests to compare the percentage of correct answers pre- and post- for the

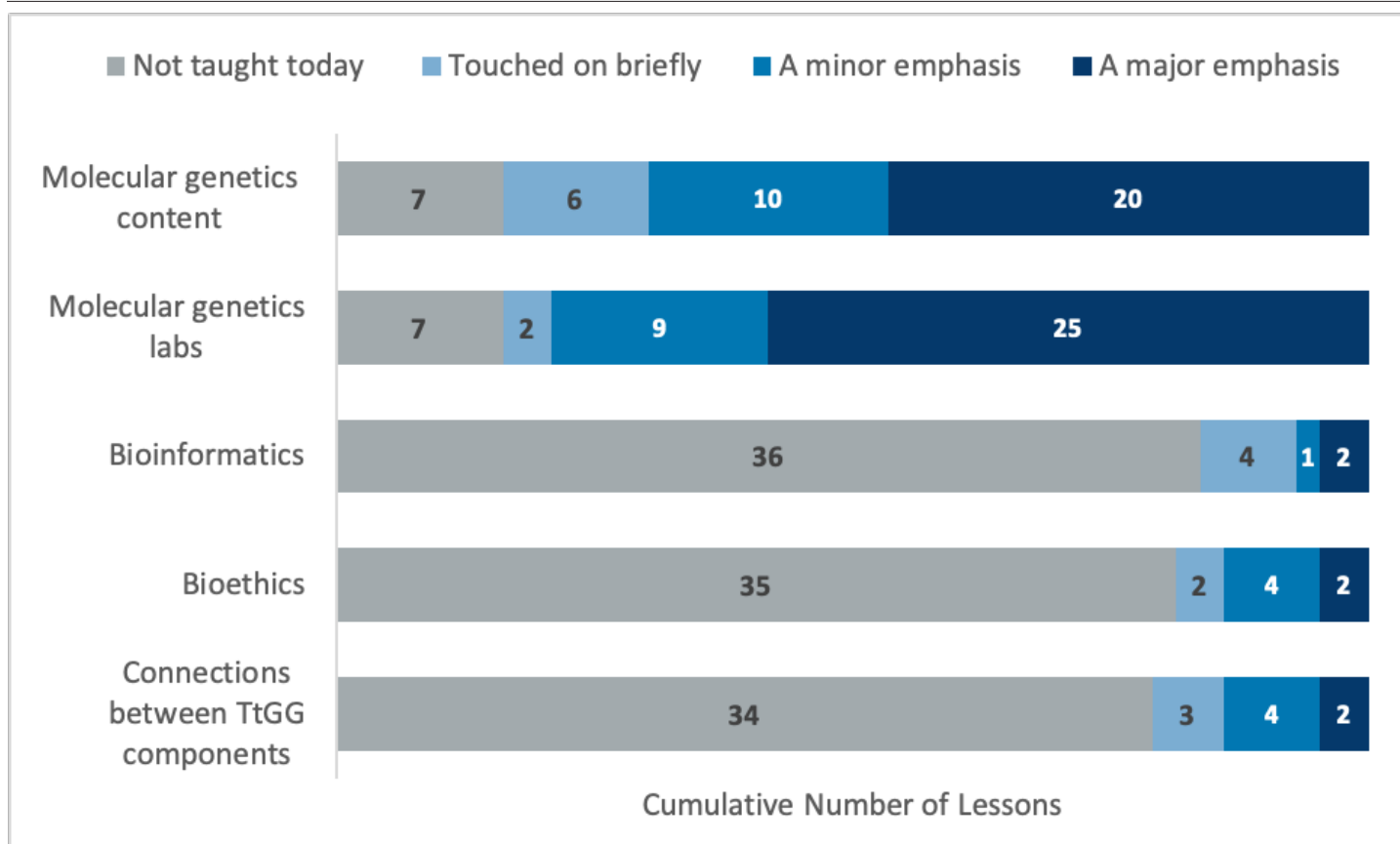


Figure 3. Level of emphasis of TtGG concepts by lesson ($N = 43$ lesson logs across 10 teachers; median = 4 logs).

full sample and by subscale. We also conducted independent samples t tests to compare the average score gain for students with experienced and novice TtGG teachers (Dimitrov & Rumrill, 2003). Because few teachers reported covering bioinformatics and bioethics topics during the study period (one and three teachers, respectively), we chose not to report these results in our manuscript.

We analyzed the attitude items individually with nonparametric statistics (Lovelace & Brickman, 2013). Because the self-efficacy items included ordinal ratings and a categorical option (“I’ve never done this before”), we conducted chi-square analyses. We compared students’ pre- and post-performance on four categories: low, moderate, or high efficacy (ratings of 1-2, 3-5, and 6-7, respectively) and no experience. The career interest item also included a categorical option (“I don’t know”), so we also analyzed it with chi-square tests. For the activity interest ratings, we conducted Wilcoxon signed rank tests.

For all sets of analyses, we applied Bonferroni corrections to control the family-wise error rate, or the likelihood of getting a “false positive” result. To do this, we divided the standard alpha value of .05 by the number of comparisons to establish a lower threshold for statistical significance. For instance, when comparing pre- and post-knowledge scores on the four subscales, we used a corrected value of .0125 (.05/4).

Qualitative Data. We applied inductive and deductive coding schemes to the open-ended survey items. We used codes from the TtGG teacher study whenever possible (LaRue et al., 2018) and added codes that emerged from the data. We coded all of the teacher items and a random 25% sample ($n = 86$) of the student responses. We reported overall codes and themes as frequencies complemented with examples of the student responses.

RESULTS

Classroom Implementation.

TtGG Components Covered. Confirming our expectations, data from the lesson logs suggested that teachers most frequently covered genetics content and lab procedures. They addressed bioethics, bioinformatics, and the connections between molecular genetics, bioethics, and bioinformatics far less often (Figure 3).

In most cases, teachers simply did not have enough time to incorporate all of the TtGG components into their instruction during the two-week window of time in which the teachers had access to the TtGG mobile laboratory kits and when we administered the student surveys. As one noted:

“Unfortunately, ninth grade biology students in [state] have to take the [state test] in biology in early

June. The curriculum required is quite lengthy and does not leave much wiggle room for extra material. While we touched on bioethics and genomics, there simply is not time for those activities in addition to the lab protocol.”

Our study design did not incorporate longitudinal tracking of teachers throughout the entire academic year, preventing us from assessing if, when, and how teachers incorporated additional bioinformatics and bioethics components of TtGG in their classes at other times.

Students’ Reactions to the Lessons. We asked students to compare their lab activities to those of bench scientists using a six-point scale (1 = very similar; 6 = very different).

- Pre: Think about the biology labs you do in class. How similar are they to the work that scientists do in their own labs?
- Post: Think about the genetics labs you just did in class. How similar were they to the work that scientists do in their own labs?

Students recognized that their TtGG labs were more similar to the work that scientists do than their typical biology labs ($n = 311$, Wilcoxon $z = 4.16$, $p < .001$, Cohen’s r effect size = .23). In fact, about three-fifths (61.5%) rated these labs as very similar or similar to scientists’ work (Figure 4). Students explained that while they used the same kinds of tools and procedures found in professional labs, their work was more basic and less sterile. The following comments were typical:

- *“While not as long, clean, and pure tests, we still used the tools and followed the steps that scientist [sic] do. And we got results also like scientists.”*
- *“Obviously we don’t have the type of lab that scientists have, but we did utilize some of their equipment, probably way less careful and clean though.”*
- *“We used the same procedure, but had the instructions written out instead of developing our own.”*
- *“I’m sure scientists use micropipettes too, and analyze their results. But their research is complicated, more thorough, and detailed.”*

Many students were interested in exploring the lesson material further. Among the 86 open-ended responses we sampled, nearly half (44.2%, $n = 38$) of the students wanted to conduct more labs. About a quarter (27.9%, $n = 24$) wanted to learn more genetics content, including information about the gene variants they had studied. Representative

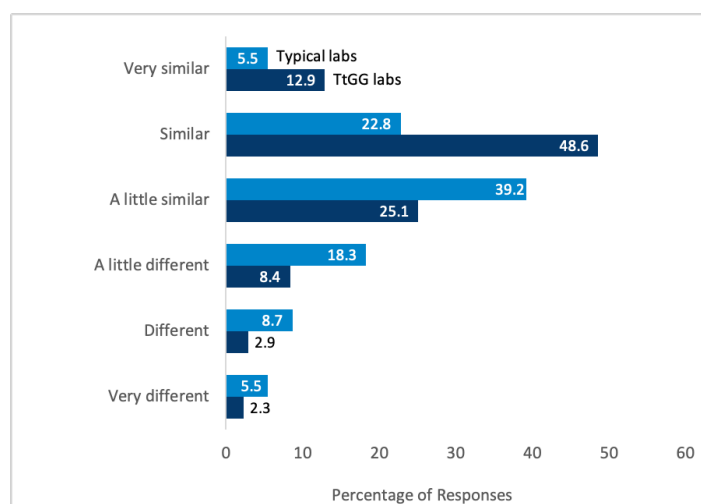


Figure 4. Students’ perceptions of the similarity of their typical biology labs and the TtGG labs to what scientists do ($n = 311$).

comments included the following:

- *“I would like to compare results to other samples, maybe from different types of people or even different species.”*
- *“I’d like to do more labs with the Pipettes.”*
- *“Can any gene be tested for using PCR?”*
- *“Is it possible to study the statistics of how many people have the ACE gene and in which proportions?”*
- *“I would like to also learn more about the ACE gene because I think it would be cool to look at someone like [former professional football player] Tom Brady and see how much of that he inherited.”*

Similarly, in 79% of the lesson logs, teachers reported that compared to their typical lessons, students were more or much more engaged in the TtGG activities (Figure 5). Comments about engagement included:

- *“At the end of each class period today I overheard many students saying that this was the most fun they have had in a class in a long time. The students walked away with an increase confidence in their ability to use molecular biology tools like micropipettes.”*
- *“They learned about the microcentrifuge, and loved it.”*
- *“Today students took away a better understanding of what the PCR process does. The lesson really hit home because of the common knowledge of PCR testing due to COVID. Students were interested in what that actually means.”*

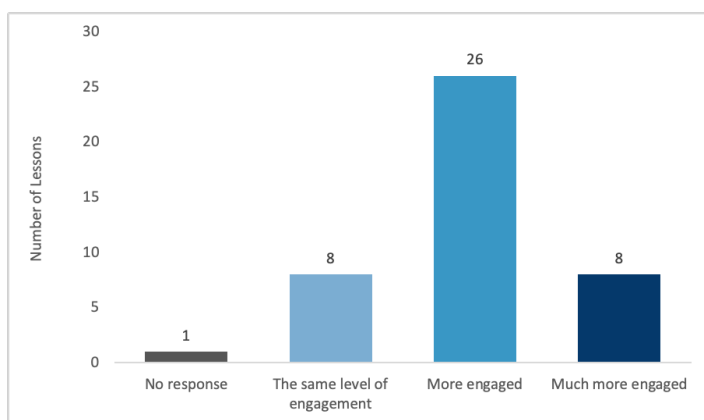


Figure 5. Level of student engagement in TtGG lessons compared to typical lessons ($N = 43$ lesson logs across 10 teachers; median = 4 logs).

Classroom Impact.

Knowledge Outcomes. Students improved their understanding of molecular genetics lab procedures, answering more multiple-choice questions correctly after the TtGG lessons (Figure 6). These gains were moderately-sized and statistically significant (paired samples $t(343) = 9.06$, $p < .001$, Cohen's d effect size = 0.49; see Table A1 in the Appendix for means and standard deviations). Students taught by more experienced teachers improved more on the procedures items than those taught by novice TtGG instructors (Score gain: independent samples $t(342) = 9.06$, $p = .001$, Cohen's $d = 0.33$; see Table A2 in the Appendix for means and standard deviations).

In their open-ended responses, 72.1% of students ($n = 62$ out of 86 sampled) identified lab procedures as one of the main things they learned. Examples included:

- “what PCR tests were”
- “I [g]ot to learn how to use a micropipette which as silly as it sounds was one of my favorite parts.”
- “how to read measurements with the pipette”
- “By analyzing the bands in DNA, I’m able to

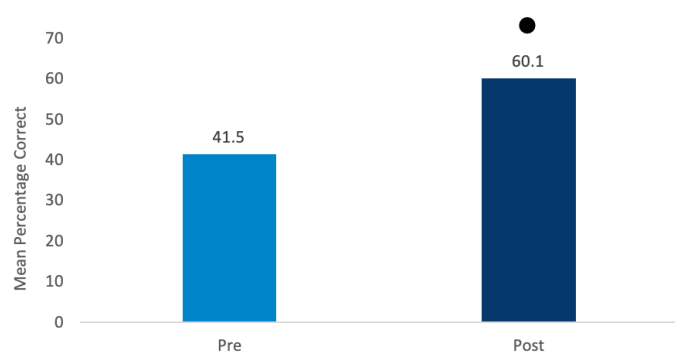


Figure 6. Average percentage correct on lab procedure items, before and after the TtGG lessons ($n = 343$ students).

● = Statistically significant pre-post difference.

determine the presence and significance of the gene.”

- “One slight mistake and the entire test is ruined.”

Nine teachers (81.8% of implementation survey responses) similarly noted that experience with lab techniques was one of the most important student learning outcomes. For example:

- “To learn how to use various genetics laboratory equipment and protocol. To analyze genetic information in ways that are meaningful and relevant to their lives.”
- “Experience with lab techniques (micropipetting; PCR; running gels) and understanding of how they work.”
- Students got to “do science” and can relate identifying a genotype into next semester’s content as well (evolution).

In contrast, students’ performance on items about molecular genetics content did not improve significantly after the lessons (paired samples $t(343) = 0.49$, $p = .626$, Cohen's $d = 0.03$; see Table A3 in the Appendix for means and standard deviations). Changes in molecular genetics scores did not vary by teachers’ level of TtGG experience. Students taught by novice TtGG teachers decreased their scores slightly ($M = -2.2$ percentage points, $SD = 22.3$), while students taught by experienced TtGG teachers increased their scores by a similar amount ($M = 1.6$, $SD = 23.4$). The difference in pre-post change between groups was not statistically significant: $t(342) = -1.35$, $p = .178$, Cohen's $d = -0.17$.

Attitude Outcomes. After the TtGG lessons, students became more confident doing lab-related activities. Their ratings significantly increased on three of the four procedure items (Figures 7a – 7d, Table 3). They started the lessons with little experience with lab tasks and became moderately or very confident after.

Table 3. Chi-Square statistics for lab procedure student self-efficacy items.

Item	<i>n</i>	$X^2(9)$	<i>p</i>	Effect Size (Cramér's <i>V</i>)
Follow written instructions in a molecular genetics lab protocol	337	46.17	< .001	.21
Describe the purpose of a PCR machine	339	14.17	.116	.12
Accurately measure samples with a micropipettor	337	24.04	.004	.15
Explain how a genotype can be determined using laboratory procedures	339	36.61	< .001	.18

Note: Cramér's *V* values between 0.10 and 0.20 are generally considered small effects, and values between 0.20 and 0.30 are moderate (Rea & Parker, 1992). As with all effect sizes, interpretations are context-dependent.

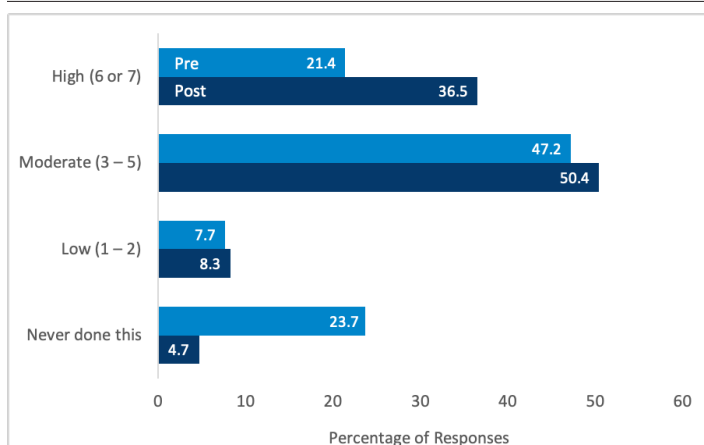


Figure 7a. Students' self-efficacy for following written instructions in a molecular genetics lab protocol, before and after the TtGG lessons ($n = 337$).

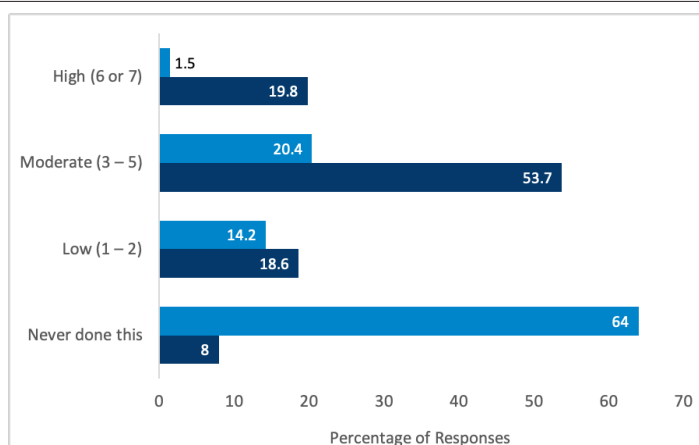


Figure 7b. Students' self-efficacy for describing the purpose of a PCR machine, before and after the TtGG lessons ($n = 339$).

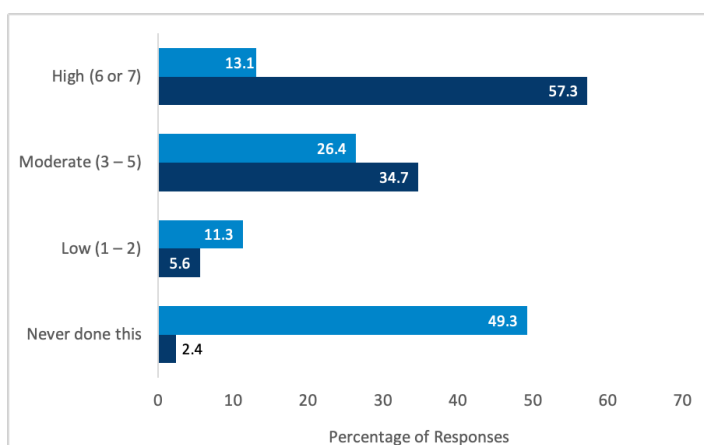


Figure 7c. Students' self-efficacy for accurately measuring samples with a micropipettor, before and after the TtGG lessons ($n = 337$).

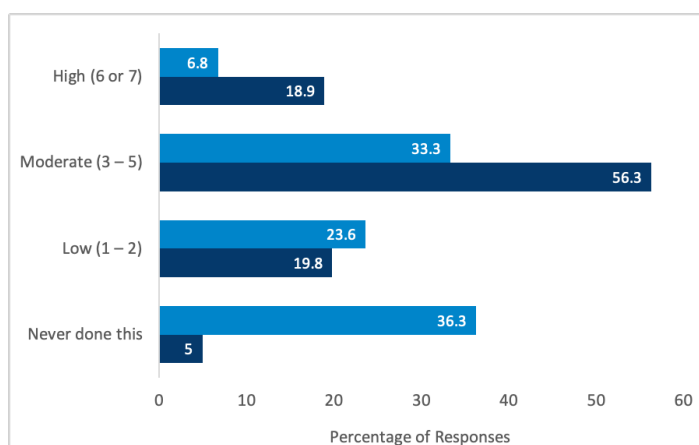


Figure 7d. Students' self-efficacy for correctly explaining how a genotype can be determined using laboratory procedures, before and after the TtGG lessons ($n = 339$).

Students also became significantly more interested in biomedical science careers (Figure 8, $X^2(25) = 310.83$, $p < .001$, Cramér's $V = .43$). Their interest in doing other genetics-related activities remained the same from pre to post, or decreased slightly. Three of the changes were statistically significant: taking a course in advanced biology, watching a YouTube video about genetics, and participating in a voluntary genetic test (See Table A4 in the Appendix for median ratings, Wilcoxon signed-ranks z statistics, and effect sizes for all activities).

CONCLUSION AND DISCUSSION

Our naturalistic study of the TtGG program highlights the curriculum's value for improving students' knowledge and attitudes around biomedical skills and increasing student engagement, both of which are important in promoting future persistence in STEM. The adaptable nature of the program allows it to be incorporated into a variety of high school biology classrooms, regardless of the teacher's level of prior experience with the curriculum.

Students Gained Biotechnology Skills Through TtGG Labs and Felt a Deeper Engagement with Genetics and Genomics Content. Our data demonstrate that students perceived the TtGG lessons as akin to what “real” scientists do in the laboratory, more so than other labs they are exposed to in their biology classes. The laboratory protocols provided by TtGG are more discovery-based as compared to traditional “cookbook” labs that are often performed in the high school classroom and the laboratory equipment provided to the schools is professional-grade. Students recognized these differences in their laboratory experience and acknowledged that the labs felt more authentic than other labs they performed in school. Teachers also perceived an enhanced level of student engagement; 79% of teacher lesson logs indicated that the TtGG lessons were more engaging than typical classroom lessons. This was echoed by student data, where nearly half of the students indicated an interest in wanting to explore the lab procedures further. Increased engagement is likely the reason why the molecular laboratory component of the TtGG program—which includes the detailed molecu-

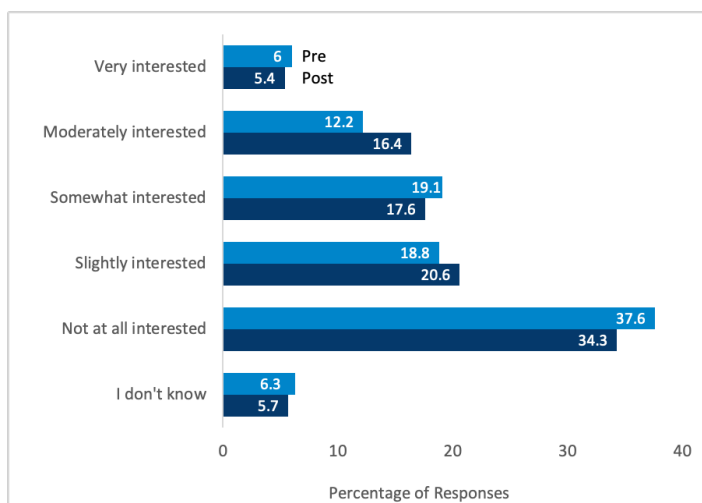


Figure 8. Students' interest in a career in the biomedical sciences, before and after the TtGG lessons ($n = 335$).

lar genetics protocols and the mobile lab kits with reagents and equipment—is consistently the most valued component of our three-armed TtGG curriculum amongst our teachers (LaRue et al., 2018). Our data supports the notion described in the literature that participatory genetics activities increase student engagement and could positively impact persistence in STEM (Graham et al., 2013; Maltese & Tai, 2011).

We also observed an increase in students' knowledge of and confidence in being able to perform biotechnology-relevant laboratory procedures. These findings suggest that TtGG is an effective and valuable approach to providing hands-on experiences that enhance interest in science while building laboratory skills that are critical to populating a future biomedical workforce. While all students experienced positive gains in laboratory skills, slightly larger gains were seen among students who were taught by experienced TtGG teachers, supporting the idea that repeat usage of the TtGG curriculum and lab materials by teachers enhances the impact that the program has on their students.

While the TtGG curriculum improved outcomes associated with genetics laboratory procedures, it had no effect on overall knowledge gains around genetics content. Our curriculum is not designed to teach foundational concepts in genetics, such as modes of inheritance and the Central Dogma, but instead shows how these concepts are applied to study phenomena of human genetic variation. Teachers are expected to provide their own lessons and activities around foundational genetics content prior to using the TtGG laboratory curriculum. Therefore, students were likely exposed to genetics content presented by their teachers outside of the study window. Without more exact information about what was taught and when, it is difficult to assess if any changes in overall content knowledge were attributable to exposure to the TtGG lessons.

We were also interested in understanding if TtGG impacted students' interest in engaging in additional genomics-related behavior, including academic and career pursuits, and assessed this through a survey containing questions exploring attitudes and behaviors. While we did not observe a significant change in most of the metrics we examined, we did find that students were slightly more interested in exploring biomedical careers after their exposure to TtGG. This suggests that if students feel that they are doing experiments and activities that “real” scientists do, and they are engaged in the experience, then they may have gained the confidence and interest to begin thinking about future biomedical careers.

TtGG Teachers Value Experiential Learning Labs, Especially with Limited Time.

Our program's use of loaner mobile lab kits dramatically increases teacher and student access to authentic biotechnology equipment for hands-on, relevant laboratory skill building. Therefore, teachers tend to prioritize the laboratory component of the curriculum over the other two strands of the TtGG program (bioethics and bioinformatics). This study took place in 2022, after one to two years of online schooling due to the COVID-19 pandemic, which could further explain why teachers emphasized the value of hands-on experiences. However, historical TtGG implementation data (2014-2024, which is not shown) confirms that the biggest draw to our program is the hands-on labs; therefore, we do not have reason to believe this was a strong confounding variable influencing teachers' use of the curriculum. Thus, it is not surprising that the significant learning gains we observed centered around the laboratory component of our curriculum.

We know that time is a major barrier to implementing new curricula in the classroom. With state and national exam requirements and the need to adhere to district-mandated curricular standards, it can be challenging for teachers to find ways to add new content to their curriculum. While this is not new or surprising, it reinforces the need for efficient curriculum and resources that teachers can easily access and use. The TtGG protocols have clear, step-by-step instructions for teachers and students with accompanying video tutorials that teachers can reference in advance of teaching their students. Since conducting this study, we have enhanced our lessons and teacher resources to highlight authentic research skills gained through genetic and genomic data analysis and interpretation of published human data in open access resources such as cBioPortal (cBioPortal, n.d.) and the SEER database (National Cancer Institute, n.d.). These non-laboratory lessons include live recorded webinars to introduce each lesson, rich teacher guides (including implementation strategies, alignment to standards, and background information), additional teacher resources such as answer keys and slides, and video tutorials for new research-based content for

use in the classroom (see Appendix for the URLs for our program website and curricular resources).

TtGG is Adaptable to a Variety of Biology Class Settings.

This study had a broad, exploratory focus, as we were interested in how teachers were using the TtGG materials in their classes and how the instruction affected students. As such, we did not prescribe exactly what teachers taught or ask that they cover particular lessons or topics. While this limited our ability to deeply study implementation fidelity, we also observed the benefit that it provided: namely, the opportunity to see the TtGG curriculum used successfully in 12 different class settings. Our data demonstrates that TtGG lessons have broad-reaching benefits when taught however the teacher thinks is most appropriate for their specific classroom. Further, we found that our program is impactful when taught by both teachers who are new to TtGG and longtime users. Students of experienced TtGG teachers showed slightly greater improvement on the laboratory procedures, indicating that continued usage of the TtGG program by teachers may build teacher confidence and skills in this area, which in turn positively impacts students. Taken together, our data shows that teachers who are new to our program should feel confident that they can have an immediate impact on their students' classroom experience after participating in our professional development program, and that continued usage of TtGG can enhance student learning gains in the lab.

Limitations and Future Directions. This naturalistic study enabled us to evaluate our program's impact without providing teachers with a prescriptive set of instructions on how to teach the curriculum. While we obtained meaningful results on our program's impact, the design also had its limitations. The study was conducted over the two-week period that teachers had access to our mobile laboratory kits so we could schedule the provision of study materials to the teachers and track completion of pre and post surveys. This tightly defined window of observation meant that we were primarily evaluating use of the laboratory elements of the curriculum. If a teacher opted to use a bioethics or bioinformatics lesson at another time in the school year before or after the lab lessons were conducted, our study design did not allow us to capture that data. Thus, our data is largely reflective of only the laboratory component of our curriculum, which we also know to be the most widely adopted element of our program.

We speculate that how we frame some of the components of the TtGG curriculum, especially during the teacher PD training, may affect how teachers perceive and categorize elements as bioinformatics and bioethics. Four participating teachers (29%) chose the *ACTN3* or *TAS2R38* gene assays which require bioinformatics protocol Sanger Sequence Analysis for genotype determination. Despite having this

“built-in” opportunity for a bioinformatics exercise, these teachers' logs fail to report using bioinformatics in the classroom. While there is a chance that teachers stopped at gel electrophoresis and truly skipped the sequence analysis step, it is also possible that, because the Sanger sequence protocol is directly part of the laboratory assays, teachers do not consider it part of the bioinformatics arm of TtGG. Similarly, all TtGG-trained teachers learn to lead conversations around informed consent while initiating the TtGG labs. This is not offered as a formal lesson plan and is instead integrated into prework for the DNA Extraction protocol. Therefore, teachers likely had these conversations but failed to label them as bioethics because the timing was concurrent with a lab. Moreover, since the teacher PD course includes trainings in additional, stand-alone TtGG bioinformatics activities and PGED-branded bioethics lessons, it would not surprise us to learn that teachers' perceptions of our three-armed program are slightly different from ours; namely, that molecular labs include all protocols in Figure 1, and bioinformatics and bioethics comprise the stand-alone lessons. In the future, we should be more specific in our lesson logs to ask teachers if they performed specific named assays, lessons, and topics, in addition to asking about these broad arms.

In designing the survey instruments for this study, we chose to use previously published content questions that had been developed for use with secondary school students rather than questions that were derived directly from the curriculum. We picked items from the GLASS that measured concepts from the labs, such as the relationship between genes, DNA, and chromosomes, and the effect of having a gene variant. As noted earlier though, students were likely exposed to these concepts before the labs, which would minimize the change we might detect in our study. Moreover, while most teachers reported that they strongly emphasized genetics content in the lessons, we do not know exactly which concepts they covered and how closely they aligned to our measures. Due to limitations of time and post-COVID restrictions around visitors in schools, the TtGG team did not directly observe the lessons and labs being taught in the classrooms. Therefore, the study relied upon teacher logs to help us understand how our lessons were used in the classroom and exactly what content was covered.

While we were encouraged by the fact that students felt that they were participating in authentic laboratory experiences when using the TtGG protocols and kits, we acknowledge that “real science” is not just about using fancy equipment. To dive deeper into the impact of the laboratory component of the curriculum, perhaps we could have added a question to the post survey that would have more broadly addressed scientific skills (Imondi et al., 2019). For example, a question such as “What was the most valuable thing you learned from the labs you just performed about the kinds of tools and methods scientists use to conduct genetics re-

search?” may have elicited responses about scientific habits of mind (e.g., precision, persistence) and given us a more expansive view of how students think science is done.

Per the conditions of our Institutional Review Board determination, teachers informed students that participation in the surveys was voluntary and that it would not impact their grades in any way. The students’ main incentive for participating in the study was to give feedback about the program to help future students. Given these limitations and the fact that we were not able to directly observe students participating in the lessons, we cannot be completely sure that students took the lessons and surveys seriously. This is part of the nature of a voluntary classroom study involving students and will always be a challenge.

While we acknowledge that the design of our evaluation study precluded us from adequately capturing data on the bioethics and bioinformatics elements of our program, we do provide recommendations for designing precise studies and instruments to evaluate knowledge outcomes in these areas. These program improvements are being implemented and have substantially informed subsequent evaluation efforts. Since this classroom study, TtGG has evolved to include a greater emphasis on data literacy and quantitative skills; several new lessons have been developed on topics ranging from cancer genetics to sequence comparison to genetic ancestry. For our future evaluation studies, we have opted to be more prescriptive in outlining exactly which lessons and activities we would like teachers to use in their classes, to obtain better fidelity across our implementation data. Further, we are designing our own assessment questions and survey instruments, creating questions that are directly aligned to the learning goals and objectives of the lessons we are evaluating. We have asked teachers who have used the bioinformatics lessons to review draft questions, giving us valuable feedback on their content and wording. Their expert advice has helped us validate the measures and ensure that we are measuring the concepts that teachers are emphasizing in the lessons (Bass et al., 2016). Finally, we have shortened the length of these surveys and converted them to an online format, to hopefully streamline the classroom study process for teachers and assist with time management.

Teaching the Genome Generation (TtGG) is an effective program to engage students in modern genetics content and help them see how authentic scientific investigations in genetics are conducted. Through partnership with teachers and lessons learned over nine years of experience, we are iteratively improving and refining the program to meet the needs of teachers and their students. With new content development and implementation by our network of teachers, the next chapter of TtGG will be an exploration of how genetic data analysis can be used to enhance students’ data literacy and quantitative skills, and contextualize those skills through real-world genetic investigations.

ASSOCIATED CONTENT

Supplemental material mentioned in this manuscript can be found uploaded to the same webpage as this manuscript.

AUTHOR INFORMATION

Corresponding Author

Sarah Wojiski (sarah.wojiski@jax.org)

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

This work is licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) License.

ACKNOWLEDGMENTS

We would like to thank Hannah Tremblay for her careful review of the manuscript and for maintaining operations of the TtGG program. We thank our colleagues at Personal Genetics Education & Dialogue (<https://pged.org/>) who partner with us in delivering important bioethics content and curricula to teachers. Most importantly, we thank all of the teachers and their students who agreed to participate in this classroom study and contribute data to this manuscript.

FUNDING SOURCES

Research and work reported in this publication were supported by the National Institute of General Medical Sciences of the National Institutes of Health under Award Number R25GM142036 from the Science Education Partnership Award (SEPA) program. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

ABBREVIATIONS

BLAST: Basic Local Alignment Search Tool; BP: Base Pair; COVID-19: Coronavirus Disease of 2019; DNA: Deoxyribonucleic Acid; ED: Department of Education; GLASS: Genetics Literacy Assessment for Secondary Schools; IRB: Institutional Review Board; JAX: The Jackson Laboratory; NCBI: National Center for Biotechnology Information; NSF: National Science Foundation. OMIM: Online Mendelian Inheritance in Man; PCAST: President’s Council of Advisors on Science and Technology; PCR: Polymerase Chain Reaction; PD: Professional Development; PGED: Personal Genetics Education & Dialogue; SEER:

Surveillance, Epidemiology, and End Results; SEPA: Science Education Partnership Award; STEM: Science, Technology, Engineering, and Mathematics; TtGG: Teaching the Genome Generation

REFERENCES

- Athanasiadis, G., Jorgensen, F. G., Cheng, J. Y., Kjaergaard, P. C., Schierup, M. H., & Mailund, T. (2016). Spitting for science: Danish high school students commit to a large-scale self-reported genetic study. *PLoS ONE*, *11*(8), Article e0161822. <https://doi.org/10.1371/journal.pone.0161822>
- Bandura, A. (2006). Guide for constructing self-efficacy scales. In F. Pajares & T. Urdan (Eds.), *Self-Efficacy Beliefs in Adolescents* (pp. 307–337). Information Age Publishing.
- Bass, K. M., Dritz-Esser, D. & Stark, L. A. (2016). A primer for developing measures of science content knowledge for small-scale research and instructional use. *CBE—Life Sciences Education*, *15*(2). Article rm2 <https://doi.org/10.1187/cbe.15-07-0142>
- cBioPortal for Cancer Genomics. (n.d.) <https://www.cbioportal.org/>
- Chang, M. J., Sharkness, J., Hurtado, S., & Newman, C. B. (2014). What matters in college for retaining aspiring scientists and engineers from underrepresented racial groups. *Journal of Research in Science Teaching*, *51*(5), 555–580. <https://doi.org/10.1002/tea.21146>
- Chapman, R., Likhanov, M., Selita, F., Zakharov, I., Smith-Woolley, E., & Kovas, Y. (2019). New literacy challenge for the twenty-first century: Genetic knowledge is poor even among well educated. *Journal of community genetics*, *10*(1), 73–84. <https://doi.org/10.1007/s12687-018-0363-7>
- Cooper, K. M., Gin, L. E., Akeeh, B., Clark, C. E., Hunter, J. S., Roderick, T. B., Elliott, D. B., Gutierrez, L. A., Mello, R. M., Pfeiffer, L. D., Scott, R. A., Arellano, D., Ramirez, D., Valdez, E. M., Vargas, C., Velarde, K., Zheng, Y., & Brownell, S. E. (2019). Factors that predict life sciences student persistence in undergraduate research experiences. *PLoS ONE*, *14*(8), Article e0220186. <https://doi.org/10.1371/journal.pone.0220186>
- Dedhia, M., Kohetuk, K., Crusio, W. E., & Delprato, A. (2019). Introducing high school students to the Gene Ontology classification system. *F1000Research*, *8*, Article 241. <https://doi.org/10.12688/f1000research.18061.4>
- Dimitrov, D. M., & Rumrill, P. (2003). Pretest-posttest designs and measurement of change. *WORK: A Journal of Prevention, Assessment, & Rehabilitation*, *20*(2), 159–165.
- Dyer, S. C., Austine-Orimoloye, O., Azov, A. G., Barba, M., Barnes, I., Barrera-Enriquez, V. P., Becker, A., Bennett, R., Beracochea, M., Berry, A., Bhai, J., Bhurji, S. K., Boddu, S., Branco Lins, P. R., Brooks, L., Ramaraju, S. B., Campbell, L. I., Martinez, M. D., Charkhchi, M., (...), & Yates, A. D. Ensembl 2025, (2025). *Nucleic Acids Research*, *53*(D1), 948–957. <https://doi.org/10.1093/nar/gkae1071>
- Estrada, M., Burnett, M., Campbell, A. G., Campbell, P. B., Denetclaw, C. G., Gutierrez, C. G., Hurtado, S., John, G. H., Matsui, J., McGee, R., Okpodu, C. M., Robinson, T. J., Summers, M. F., Werner-Washburne, M., & Zavala, M. (2017). Improving underrepresented minority student persistence in STEM. *CBE—Life Sciences Education*, *15*(3). Article es5 <https://doi.org/10.1187/cbe.16-01-0038>
- Gandhi-Lee, E., Skaza, H., Marti, E., Schrader, P. G., & Orgill, M. (2017). Faculty perceptions of student recruitment and retention in STEM fields. *European Journal of STEM Education*, *2*(1), Article 2. <https://doi.org/10.20897/es-teme.201702>
- Garber, K. B., Hyland, K. M., & Dasgupta, S. (2016). Participatory genomic testing as an educational experience. *Trends in Genetics*, *32*(6), 317–320. <https://doi.org/10.1016/j.tig.2016.03.008>
- Graham, M. J., Frederick, J., Byars-Winston, A., Hunter, A. B., & Handelsman, J. (2013). Increasing persistence of college students in STEM. *Science*, *341*(6153), 1455–1456. <https://doi.org/10.1126/science.1240487>
- Haladyna, T. M., Downing, S. M., & Rodriguez, M. C. (2002). A review of multiple-choice item-writing guidelines for classroom assessment. *Applied Measurement in Education*, *15*(3), 309–333. https://doi.org/10.1207/S15324818AME1503_5
- Harvard Medical School. (n.d.). Personal Genetics Education & Dialogue (PGED). <https://pged.org/>
- Hicks, M. A., Cline, R. J., & Trepanier, A. M. (2014). Reaching future scientists, consumers, & citizens: What do secondary school textbooks say about genomics & its impact on health? *The American Biology Teacher*, *76*(6), 379–383. <https://doi.org/10.1525/abt.2014.76.6.5>
- Imondi, R., Bass, K. M., Patel, R., & Santschi, L. (2019). NeuroLab research experiences: Extending the CURE design framework to an informal science setting devoted to pre-college STEM instruction. *Journal of STEM Outreach*, *2*(1), 1–14. <https://doi.org/10.15695/jstem/v2i1.08>
- Institute of Education Sciences, U.S. Department of Education, & National Science Foundation (2013). *Common Guidelines for Education Research and Development: A Report from the Institute of Education Sciences, U.S. Department of Education, and the National Science Foundation*. www.nsf.gov/pubs/2013/nsf13126/nsf13126.pdf
- Johns Hopkins University. (n.d.). OMIM: An online catalog of human genes and genetic disorders. <https://www.omim.org/>
- Keyes, J. (2019). *Development and psychometric analysis of instrument to measure high school genetics knowledge: GLASS: Genetics Literacy Assessment for Secondary Schools*. [Unpublished Master's thesis, Stanford University].

- LaRue, K. M., McKernan, M. P., Bass, K. M., & Wray, C. G. (2018). Teaching the genome generation: Bringing modern human genetics into the classroom through teacher professional development. *Journal of STEM Outreach*, 1(2), 48–60. <https://doi.org/10.15695/jstem/v1i1.12>
- Linderman, M. D., Suckiel, S. A., Thompson, N., Weiss, D. J., Roberts, J. S., & Green, R. C. (2021). Development and validation of a comprehensive genomics knowledge scale. *Public Health Genomics*, 24(5-6), 291–303. <https://doi.org/10.1159/000515006>
- Lovelace, M. & Brickman, P. (2013). Best practices for measuring students' attitudes toward learning science. *CBE-Life Sciences Education* 12(4), 606–617. <https://doi.org/10.1187/cbe.12-11-0197>
- Maltese, A. V., & Tai, R. H. (2011). Pipeline persistence: Examining the association of educational experiences with earned degrees in STEM among U.S. students. *Science Education Policy*, 95(5), 877–907. <https://doi.org/10.1002/sce.20441>
- Martins, A., Fonseca, M. J., & Tavares, F. (2018). Mining the genome: Using bioinformatics tools in the classroom to support student discovery of genes. *The American Biology Teacher*, 80(8), 619–624. <https://doi.org/10.1525/abt.2018.80.8.619>
- Michael, A. G., Salmon, K. R., Testorf, M. E., Morrone, M., Bass, K. M., & Faletra, P. (2021). STEM lab on a kitchen table: An investigation of remote student-driven problem-based research. *Journal of STEM Outreach*, 4(2), 1–12. <https://doi.org/10.15695/jstem/v4i2.10>
- NIH National Cancer Institute. (n.d.). Surveillance, Epidemiology, and End Results Program (SEER). <https://seer.cancer.gov/>
- NIH National Library of Medicine, National Center for Biotechnology Information. Basic Local Alignment Search Tool (BLAST). (n.d.a). <https://blast.ncbi.nlm.nih.gov/Blast.cgi>
- NIH National Library of Medicine, National Center for Biotechnology Information. NCBI. (n.d.b). <https://www.ncbi.nlm.nih.gov/>
- National Science Foundation. (2007). *National action plan for addressing the critical needs of the U.S. science, technology, engineering, and mathematics education system*. (NSB 07-114). National Science Foundation. <https://nsf.gov/resources/nsf.gov/pubs/2007/nsb07114/nsb07114.pdf>
- Ormond, K. E., Hudgins, L., Ladd, J. M., Magnus, D. M., Greeley, H. T., & Cho, M. K. (2011). Medical and graduate students' attitudes toward personal genomics. *Genetics in Medicine*, 13(5), 400–408. <https://doi.org/10.1097/GIM.0b013e31820562f6>
- President's Council of Advisors on Science and Technology. (2012). *Engage to excel: Producing one million additional college graduates with degrees in science, technology, engineering, and mathematics*. Executive Office of the President. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_2-25-12.pdf
- Rea, L. M., & Parker, R. A. (1992). *Designing and conducting survey research: A comprehensive guide*. Jossey-Bass.
- Reeves T. D., & Marbach-Ad, G. (2016). Contemporary test validity in theory and practice: A primer for discipline-based education researchers. *CBE-Life Sciences Education*, 15(1), Article rm1. <https://doi.org/10.1187/cbe.15-08-0183>
- Salari, K., Karczewski, K. J., Hudgins, L., & Ormond, K. E. (2013). Evidence that personal genome testing enhances student learning in a course on genomics and personalized medicine. *PLoS ONE*, 8(7), e68853. <https://doi.org/10.1371/journal.pone.0068853>
- Sanderson, S. C., Linderman, M. D., Kasarskis, A., Bashir, A., Diaz, G. A., Mahajan, M. C., Shah, H., Wasserstein, M., Zinberg, R. E., Zweig, M., & Schadt, E. E. (2013). Informed decision-making among students analyzing their personal genomes on a whole genome sequencing course: A longitudinal cohort study. *Genome Medicine*, 5, Article 113. <https://doi.org/10.1186/gm518>
- Smith, M. (2014a). It's not your grandmother's genetics anymore! *The American Biology Teacher*, 76(4), 224–229. <https://doi.org/10.1525/abt.2014.76.4.2>
- Smith, M. (2014b). It's not your grandmother's genetics anymore (Part 2)! *The American Biology Teacher*, 76(5), 306–310. <https://doi.org/10.1525/abt.2014.76.5.3>
- Stern, F., & Kampourakis, K. (2017). Teaching for genetics literacy in the post-genomic era. *Studies in Science Education*, 53(2), 193–225. <https://doi.org/10.1080/03057267.2017.1392731>
- U.S. Department of Education. (2015). *Science, technology, engineering, and math: Education for global leadership*. <https://www.ed.gov/media/document/stem-overviewpdf>
- van Lieshout, E., & Dawson, V. (2016). Knowledge of, and attitudes towards, health-related biotechnology applications amongst Australian Year 10 high school students. *Journal of Biological Education*, 50(3), 329–344. <https://doi.org/10.1080/00219266.2015.1117511>
- Vernez, S. L., Salari, K., Ormond, K. E., & Lee, S. S. J. (2013). Personal genome testing in medical education: Student experiences with genotyping in the classroom. *Genome Medicine*, 5, Article 24. <https://doi.org/10.1186/gm428>
- Weber, K. S., Jensen, J. L., & Johnson, S. M. (2015). Anticipation of personal genomics data enhances interest and learning environment in genomics and molecular biology undergraduate courses. *PLoS ONE*, 10(8), Article e0133486. <https://doi.org/10.1371/journal.pone.0133486>
- Weber, K. S., Bridgewater, L. C., Jensen, J. L., Breakwell, D. P., Nielsen, B. L., & Johnson, S. M. (2018). Personal microbiome analysis improves student engagement and interest in immunology, molecular biology, and genomics undergraduate courses. *PLoS ONE*, 13(4), Article e0193696. <https://doi.org/10.1371/journal.pone.0193696>

- Whitley, K. V., Tueller, J. A., & Weber, K. S. (2020). Genomics education in the era of personal genomics: Academic, professional, and public considerations. *International Journal of Molecular Sciences*, 21(3), Article 768. <https://doi.org/10.3390/ijms21030768>
- Yang, X., Hartman, M. R., Harrington, K. T., Etson, C. M., Fierman, M. B., Slonim, D. K., & Walt, D. R. (2017). Using next-generation sequencing to explore genetics and race in the high school classroom. *CBE—Life Sciences Education*, 16(2), Article ar22. <https://doi.org/10.1187/cbe.16-09-0281>