CITIZEN SCIENCE:
THEORY AND PRACTICE

Expanding the Scope of Citizen Science: Learning and Engagement of Undergraduate Students in a Citizen Science Chemistry Lab

SPECIAL COLLECTION:
CITIZEN SCIENCE IN HIGHER EDUCATION

RESEARCH PAPER

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ABSTRACT

The COVID-19 pandemic has placed public health and wellbeing at the forefront of public concerns and interests, transforming the ways people interact and engage with science. One way to support and expand such engagement is through citizen science, which has seen huge growth over the past decade. Since many scientific fields are still largely underrepresented within citizen science, this paper explores the expansion of citizen science into new fields and settings. The study examines the learning processes and outcomes of students participating in a lab-based chemistry citizen science initiative, *Breaking Good*, and explores the "why," "how," and "what" of laboratory learning.

Our findings reveal a dynamic learning environment characterised by the hands-on, authentic, and novel science experience within these labs. The broader context afforded by a citizen science approach was found to enhance student knowledge of course content and knowledge of both the process and nature of science alongside increased motivation. As universities are ideally placed to incorporate citizen science into higher education teaching, this paper calls for research institutions to take a leading role in this process, promoting student learning and the development of scientific fields by expanding the scope of citizen science.

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BACKGROUND

The rapidly growing field of citizen science has demonstrated potential to advance outcomes for science, society, and individuals (Shirk et al. 2012; Turrini et al. 2018). On an individual level in particular, citizen science is an effective avenue for learning across a range of settings, with evidence suggesting that engagement can increase science knowledge, awareness, and appreciation (National Academies of Sciences Engineering and Medicine 2018; Phillips et al. 2018b). In a formal educational context, citizen science empowers students to learn disciplinary content and skills while engaging in authentic research. Citizen science can also foster effective processes of public engagement with science and lead to meaningful socio-scientific outcomes and agency (Ballard, Dixon and Harris 2017; Wals et al. 2014).

However, to fully realise the outcomes outlined above, detailed work is needed in the specific design and delivery of projects in formal education settings (National Academies of Sciences Engineering and Medicine 2018). Facilitators of citizen science (those who lead, train, or educate groups of participants within a citizen science project) play an important role in shaping student participation and learning (Lorke et al. 2019). Facilitators connect project participants with project designers or researchers, and can have a significant impact on participant experience, often building from their own experiences and expertise to shape their teaching approach and content. For example, Golumbic et al. (2021) describe the important role that enthusiastic facilitation by teachers plays in driving student learning and motivation in the Radon Home Survey. Furthermore, by guiding students to make connections between the data they collect, their community, and daily life, learning is enhanced and the work they conduct is more meaningful (Jenkins 2011).

In line with the above, universities across the globe are increasingly embedding citizen science into undergraduate curricula to improve student engagement and learning outcomes. Some examples include ClimateWatch in Australia (Mitchell et al. 2017), BOKUroadkill in Austria (Heigl and Zaller 2014), and Cyclone Center in the USA (Phillips et al. 2018a). Each exemplify the rich opportunities for student learning enabled by citizen science including "challenge, activity, curiosity, control, imagination, cooperation, competition, and recognition" (Heigl and Zaller 2014, pp. 173).

The disciplines reflected in citizen science projects embedded within higher education reflect general trends in citizen science, dominated by biodiversity and environmental studies. Despite the huge growth of citizen science over the past decade, many scientific fields such as medicine, chemistry, and physics are still largely underrepresented within citizen science projects (Pelacho et al. 2021). As academics based in a school of chemistry, we are cognizant of the inherent challenges in embedding some areas of chemistry in citizen science, most notably those that relate to safety, and the cost or inaccessibility of necessary laboratory equipment and facilities or necessary training. A higher education setting mitigates these challenges by utilizing existing resources, laboratories, and equipment that are readily available and dedicated for student learning and training.

Research into course-based undergraduate research experiences (CUREs) provides useful examples for the incorporation of authentic research experiences in undergraduate chemistry studies. CUREs embedded in the natural sciences enable students to collect or analyse novel experimental data, following a structured inquiry process and addressing research questions to which the expected outcome is unknown (Dolan 2016; Kerr and Yan 2016). For example, Cruz et al. (2020) describe a series of undergraduate laboratory experiments centred around the synthesis and characterization of pyrylium salts in the context of photoredox catalysis with an unknown structure–activity relationship. While CUREs are not formally defined as citizen science, recent publications highlight the similarities between the fields, incorporation of citizen science projects into CUREs, and the possible expansion of CUREs into citizen science projects that have greater public engagement and stronger scientific goals (Gastreich 2020; Sorensen et al. 2018).

In the context of this paper, we define chemistry-based citizen science projects as those that include people without tertiary qualifications in chemistry working on projects that involve the study or exploration of matter and the changes it can undergo. We assert that CUREs can be classified as citizen science where they a) are part of broader projects with a focus on enabling non-scientists to participate in science and b) possess central aims that extend beyond the education and training of people studying to be scientists. We describe the Breaking Good citizen science initiative (*https://www.breakinggoodproject.com*), which empowers members of the public to be active researchers in projects that improve human health, and its incorporation into undergraduate studies. This paper discusses the expansion of citizen science into an undergraduate chemistry lab course at the University of Sydney, where students take part in the Breaking Good initiative and synthesize new drug candidates as part of a broader open source drug discovery research consortia. This setting provides a novel contribution to literature on real-world research contexts for student education while expanding the scope of citizen science to areas such as chemistry and public health.

The aim of this study was to gain a better understanding of student learning experiences and outcomes through engagement with citizen science within the context of Breaking Good. We build on the work of Jennett et al (2016), who interviewed researchers and participants from seven technology-based citizen science projects to investigate how and what the participants learnt, and then developed a thematic map for this learning. Here, we examine both how and what students learnt through participation in the Breaking Good laboratory program. We also extend this work to investigate why—illustrating and recognising the importance of the unique project environment that facilitates the learning processes identified. Our findings reveal important opportunities for the expansion of citizen science to chemistry research in higher education settings and to facilitate holistic learning for students that leads to positive influences on future career choice and engagement with science.

METHODS

RESEARCH SETTING

This study was conducted as part of the Breaking Good citizen science initiative, which originated as an educational and outreach arm of the Open Source Malaria consortium (OSM; *http://opensourcemalaria.org*). Grounded in open science principles (Todd 2019), OSM is attempting a new approach to finding new medicines for malaria, in which all data and laboratory notebooks are openly available, and anyone can participate and contribute. This approach offers a unique educational opportunity to involve undergraduates and the public in drug discovery, an area of research that is otherwise largely veiled in secrecy (Robertson et al. 2014). Over the years, OSM has engaged undergraduates from Australia, the United States, India and the United Kingdom to "*make molecules that matter,*" which were then screened against the malaria parasite with some student-generated data included in OSM's first synthetic paper (Motion (nee Williamson) et al. 2016). In 2016, the team collaborated with high school students to recreate the price-hiked drug Daraprim, and at that time, the Breaking Good moniker was coined (Motion (nee Williamson) 2017; Strom 2016). To date, Breaking Good includes lab-based projects that explore the synthesis of new drug candidates (*https://www.breakinggoodproject.com/synthesis*) and re-creation of expensive medicines, as well as a newer online project, E$$ential Medicine$, that invites citizens to contribute to a project exploring the accessibility of the world's most important medicines.

This study focuses on undergraduate Special Studies Program (SSP) students at the University of Sydney, who participated in the lab-based Breaking Good program as part of their first-year laboratory training during 2020. Over a 5-week laboratory course, students were guided by laboratory demonstrators (PhD students or postdoctoral researchers) through the synthesis of brand-new molecules that are evaluated as part of OSM. Students have contributed to the synthesis of new analogues from the Triazolopyrazine family of molecules, which have been found to display promising antimalarial properties (*https://www.breakinggoodproject.com/synthesis*).

The structure of the 5-week SSP lab is detailed in ***Figure 1***. Briefly, students spent 9 hours in total synthesising potential medicines, based on routes identified by the OSM consortium (*https://github.com/OpenSourceMalaria*). Students then took part in an analysis workshop where they learnt and applied techniques to determine whether they have successfully synthesised the molecule assigned to their team. Students were assessed on the quality of their experimental write-ups in open electronic lab notebooks, on their answers to weekly chemistry questions, and on a final science communication task in which they created a video describing their research to senior high school students.

The authors of this paper took leading roles in the design of the SSP course but were not directly involved in teaching in 2020. The second author of this paper is the initiator and director of Breaking Good and has previously headed the SSP labs (2015–2019). In 2020, a new lab head was introduced to the course who had not previously engaged with Breaking Good.

This research study took place in some of the first in-person laboratory classes after COVID-19 social distancing requirements led to a shift to online learning. Although this laboratory course had run for the five previous years, the setting provided a unique context for learning about medicines at a time in which a pandemic placed public health and wellbeing at the forefront of public concerns and interests, transforming the ways people interact and engage with science (Huang and Yang 2020). World events reinvigorated discussions about inequalities in access to science, medications, and vaccines (Germain and Yong 2020; Patel et al. 2020), and highlighted the lack of tools, knowledge, and information for people to make informed science-based decisions related to their daily lives (Dawson 2018; Silva et al. 2020).

RESEARCH PARTICIPANTS

The research population for this study are SSP students taking part in the Breaking Good labs during 2020 (N = 37) and their respective lab instructors (N = 5). The cohort was smaller than previous years due to limitations in laboratory class sizes owing to social distancing rules in place to mitigate risk during the COVID-19 pandemic. All SSP students and Breaking Good lab instructors were invited

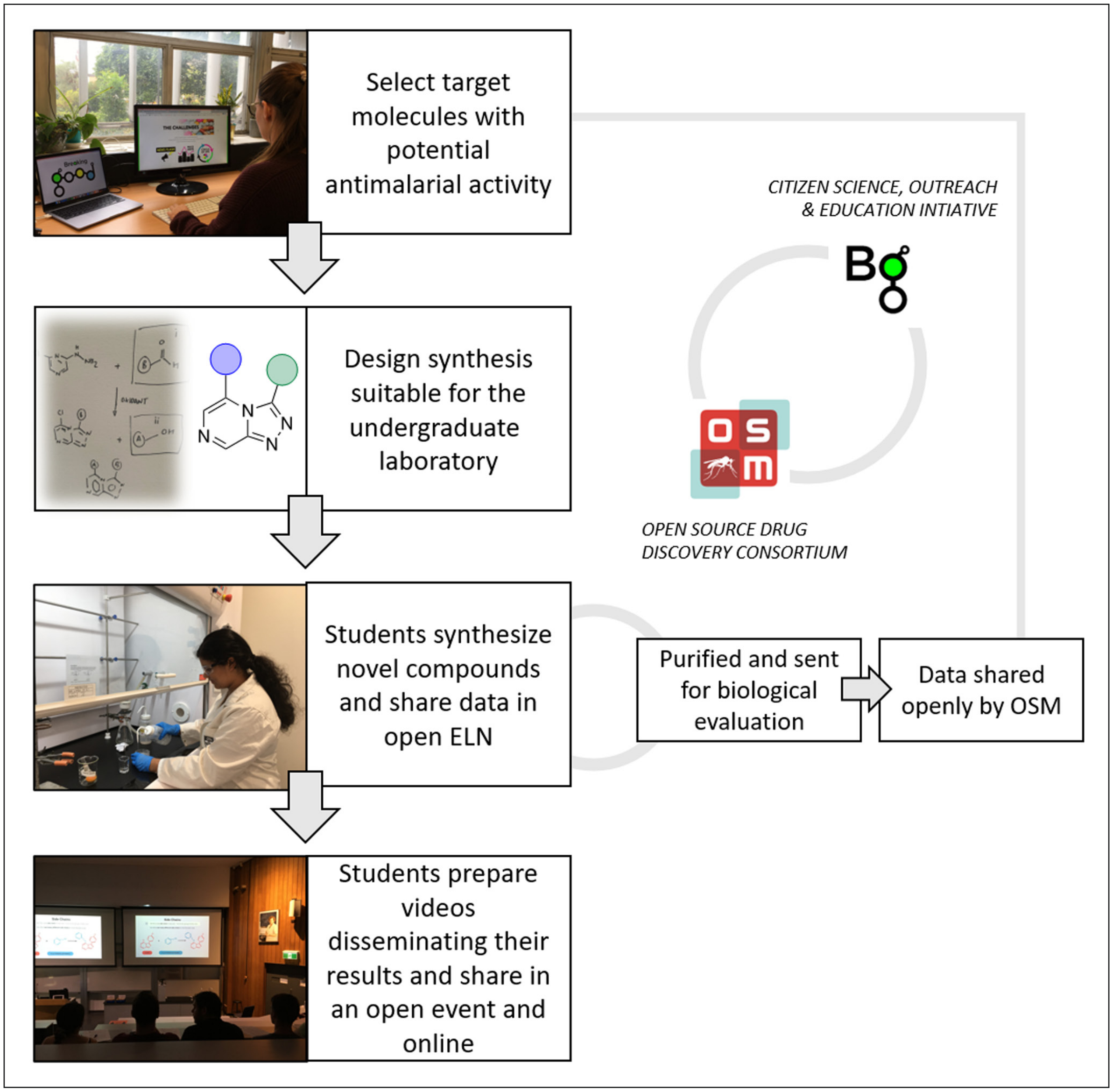

Figure 1 Structure of the Breaking Good Special Studies Program (SSP) Laboratory.

to take part in this study examining student learning experiences and processes through lab participation. A total of N = 10 students (6 men, 4 women) self-selected to be interviewed for this study, consisting of 27% of the students in the 2020 cohort. All lab instructors (N = 5; 3 men, 2 women) agreed to participate in this study. Of these, one participant was the lab head and the remaining four were lab demonstrators.

RESEARCH TOOLS, DATA COLLECTION, AND ANALYSIS

The main research tools used for this study were lab observations and semi-structured interviews with the students participating in Breaking Good labs and with their lab instructors. We chose these tools as they draw together participation experiences from both external (observations) and internal (interviews) perspectives, and provide a data richness that enables in-depth exploration of data and identification of common themes from different sources (Patton 1999).

Data collection spanned the duration of the lab experience from October to November 2020. An IRB approval was obtained from the authors' institutional committee (approved May 2020).

Interviews

Semi-structured interviews were conducted with lab instructors before or during the first two weeks of the lab course. These interviews conducted individually via Zoom were typically 45 minutes in length and focused on the instructors' role as facilitators and teachers. Interviews with students were conducted in the week following the final lab session. These 20–30 minute interviews were conducted individually via Zoom and focused on student experience, satisfaction, and learning outcomes. Interview protocol questions are detailed in Supplemental File 1: Lab instructor interview protocol.

All interviews were recorded, transcribed, and qualitatively analysed using NVivo Qualitative Data Analysis Software (QSR International Pty Ltd. 2018) to identify emerging themes using thematic analysis (Braun and Clarke 2006; Guest, MacQueen, and Namey 2012). Clusters of recurring issues were categorised, grouped, and then used to identify the processes of learning taking place through participation in the project. This inductive approach enabled the exposure of underlying ideas and patterns in the transcribed text (Thomas 2006), leading to the development of a pathway that demonstrates student learning trajectories. Quotations throughout this manuscript represent the most common and substantial themes that emerged during data analysis and are reflective of interviewees' experiences. Quotes are followed by the letters S or I, indicating student (S) or instructor (I), and a number, which has been allocated to each participant.

Lab observations

During the 5-week lab course, the first author conducted real-time observations of lab work, and in-lab interactions and discourse. During these observations, key events such as content learned, discussions, instruction style, and questions raised were noted in a field diary. These observations were used to provide a clearer context to aid analysis of the data collected through interviews and to ground the learning dimensions identified. This was achieved by closely examining the observation notes, focusing on the themes identified through the initial thematic analysis of interviews, and using this to refine the organisational framework used to categorise findings (Patton 1999). Observations also provided insight into the progression of learning over time, contributing to the identification of learning processes (Angrosino and Rosenberg 2011).

RESULTS

The overall goal of this study was to investigate student learning processes through their participation in a lab-based citizen science project. For the purposes of both our educational design and research analysis, the student learning trajectory has been broken down into three distinct areas of consideration—Why, how, and what do students learn (***Figure 2***) (Jennett et al. 2016)—each of which are outlined and explored here.

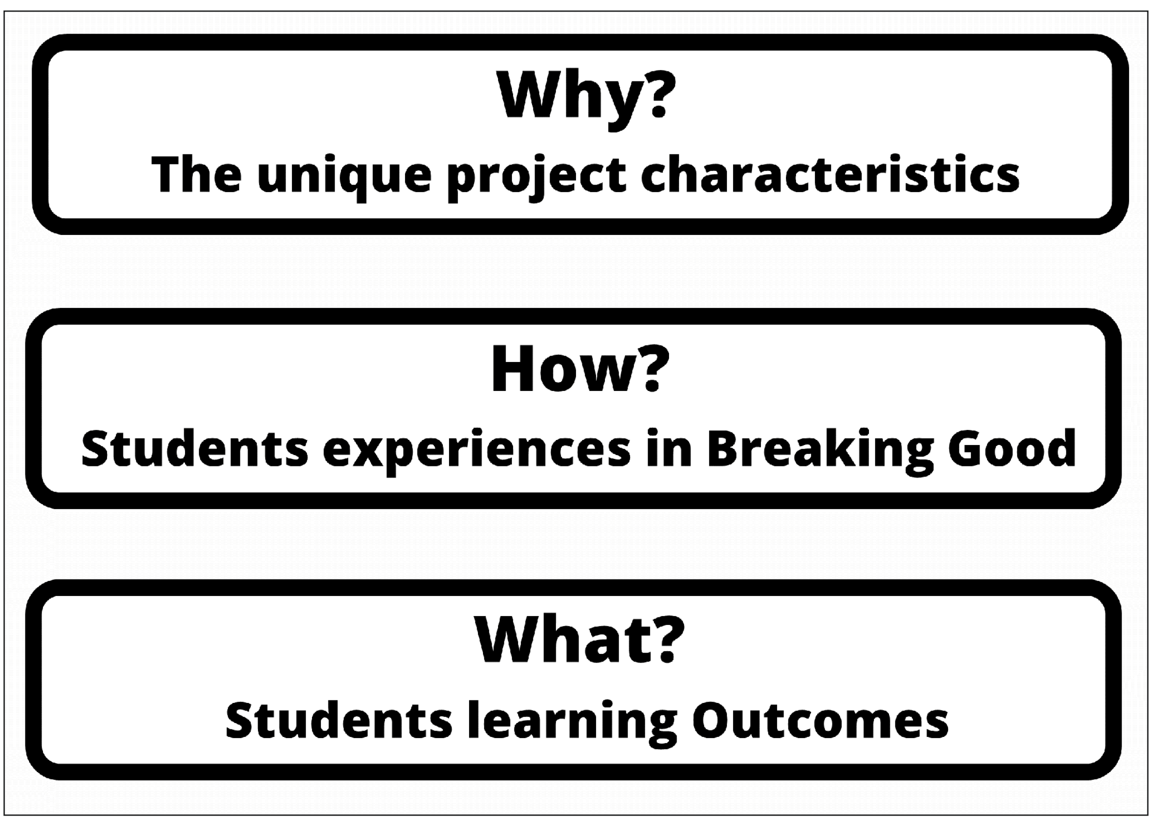

Figure 2 Outline of students learning processes and outcomes.

WHY LEARN THROUGH BREAKING GOOD? UNIQUE PROJECT CHARACTERISTICS

In an extension of the work of Jennett et al. (2016) and as foreshadowed by Kloetzer et al. (2021) we were keenly interested in exploring the impact of the unique project characteristics of Breaking Good, and the impact of these characteristics on the learning processes experienced by students. Investigating the "why" of learning requires an understanding of the project context, as seen from the perspectives of students, and it enabled us to explore the role this had in facilitating learning.

As described in the "Research setting" section, Breaking Good engages students in the synthesis of novel molecules that are investigated as potential antimalarial drug candidates. This setting provides an energising environment for student engagement and consequential learning as detailed in ***Figure 3***. Students identified the characteristics of the project as 1) a synthesis-based drug discovery project that is 2) authentic, 3) novel, and 4) important.

Participation in the project includes following a predefined synthetic pathway and engaging in hands-on organic chemistry research while learning about the drug discovery process. Students and instructors defined their engagement and involvement in the lab as follows:

> *"We synthesized a novel, antimalarial compound that's now been sent to be biologically tested. And what we did was we spent the first week synthesizing triazolopyrazine core […] and then the next two weeks, we spent adding in a specific alcohol that allowed us to create that novel, antimalarial compound. And then our final week, we took the compound we created and ran it through a range of spectroscopic analysis techniques, so like mass spectroscopy, and NMR, and stuff like that, that helped us confirm the identity of what we created" (S3); and*

> *"I teach the SSP lab classes. So, I teach them proper processes, you know, proper lab techniques. And also the chemistry behind the thing that they are doing. To not follow the recipe blindly, just to understand what's going on inside, why they're doing that, why it's important, what's the outcome of this? What they can learn from doing this?" (I3).*

One of the dominant themes discussed by students was the authentic nature of the project, which is in stark contrast to the typical undergraduate science laboratory experience. This, as indicated by students, represents a novel way to engage in laboratory learning and to be part of an open source drug discovery initiative:

> *"Breaking Good project encompasses bringing research together and the whole open source ideas. So, like, the fact that different people can make different contributions to research and that research isn't this thing that only a select group of people have access to research and the general public doesn't. It's kind of inviting more than just a group of people to not only learn about science, but contribute to science" (S5); and*

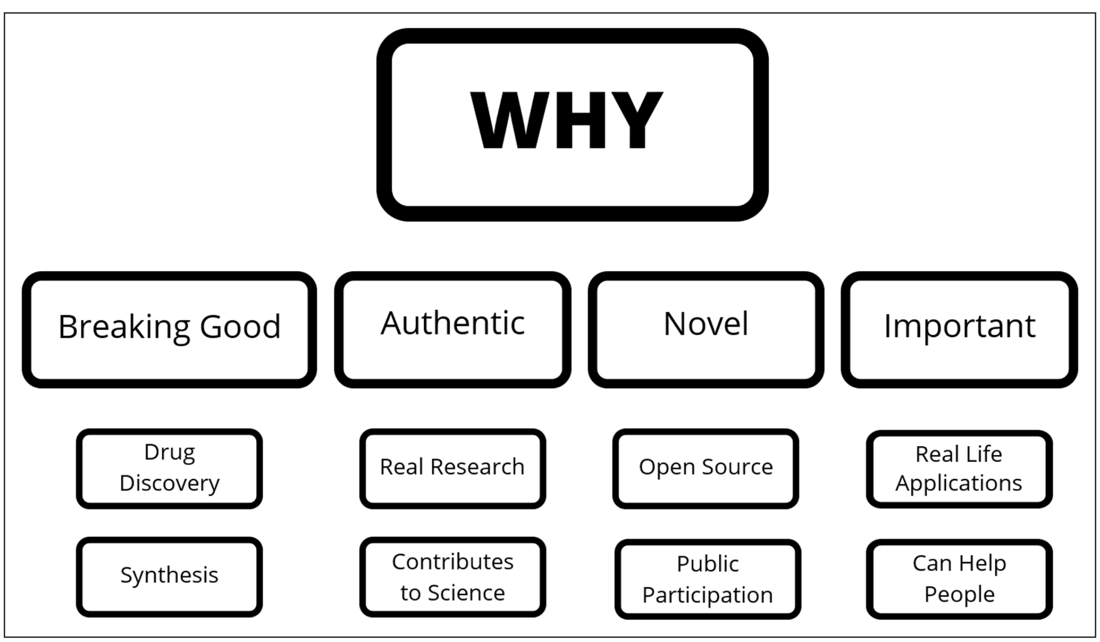

Figure 3 The unique project characteristics.

> *"It's an open source project, where people, anyone that's interested in science really can participate in experiments and labs, where they can create molecules that contribute towards that open source database for finding new cures" (S3).*

Students were particularly excited to engage in a project with real-life applications that contributes to scientific knowledge. Typical undergraduate laboratory learning rarely has this broader context, and students were empowered to contribute to something that extended beyond graded assignments. Students indicated that participating in Breaking Good felt like a good use of their time and the university resources, because samples they prepared contributed to ongoing drug discovery research:

> *"It was fun being in labs and doing proper chemistry. And it's cool knowing that it's actually getting used and getting tested on, in the end. It's not just going in the hazardous waste container" (S8).*

Students also indicated the significance and sense of reward they felt from synthesising molecules that could potentially contribute to a malaria treatment for people living in endemic countries:

> *"In Breaking Good, once my team and I made this drug, there's a potential for it to go off and maybe help some other people. So, there's a lot more weight to the stuff that we're doing" (S10); and*

> *"It's really kind of nice to be a part of something that could be so useful for so many people. I think it's quite amazing at such a young age as well, just to be a part of an opportunity like that" (S5).*

This context served as an enabler for participating students, providing additional motivation and incentive to engage with the project and to learn about its context. Students indicated this was an inspiring and rewarding experience that exposed them to many new ideas and broadened their perspectives. The distinctive context of the project and its perceived importance motivated students to work hard and carry on even when things became difficult:

> *"I think when we have high school chemistry, or when you have other advanced chemistry labs, it feels a little bit meaningless sometimes, because you're just doing that chemical reaction. But it doesn't lead to anything, the chemicals will get thrown out afterwards, you write a lab book, and then you submit that. But knowing that your product could actually go on to help people, or at least advance research was really rewarding. And that was a really key part that kind of kept driving me forward. Even when my reaction was in wrong angle or I was getting the wrong product or something like that, and I kind of wanted to give up. Knowing that really made me happy and kept me going forward" (S2).*

Taken together, the project context, authentic nature, perceived importance, and innovative design positively impacted student experiences in the laboratory and their consequential learning process and outcomes.

HOW DOES LEARNING TAKE PLACE? STUDENT EXPERIENCES OF BREAKING GOOD

Through participation in Breaking Good, students encountered a variety of practices, research methods, and scientific information that facilitated their learning and experiences. We refer to these processes as the "how" of learning, which encompasses a number of sub-themes: 1) the introduction of new lab techniques and equipment for students in addition to methods for the documentation of experimental processes, data, and analysis; 2) collaborative work in groups; 3) ongoing instruction; and 4) access to learning resources to support their progress, which was ultimately assessed through course assignments (See ***Figure 4***).

The hands-on nature of the course is an important factor in student learning processes, and is especially evident when compared with the frontal and textbook learning they have more commonly experienced. Students noted their excitement about learning new techniques, engaging in synthetic procedures, and learning more about how chemistry works by running new reactions and analyzing the resulting compounds. Some students indicated that their favourite part of the project related to the experience of physically working in the lab, using advanced equipment, and conducting high-level lab-techniques:

> *"I really liked just being in the fume hood, like adding things together and seeing the way that a reaction can transform" (S5); and*

> *"It was really interesting using all these new different functions, like the TLC and finally getting to use a separating funnel, which I saw so many times in high school" (S7).*

By participating in this project, students were provided with the opportunity to see how research is conducted in a university setting and to visit the University's research facilities. One of the student-indicated highlights of the

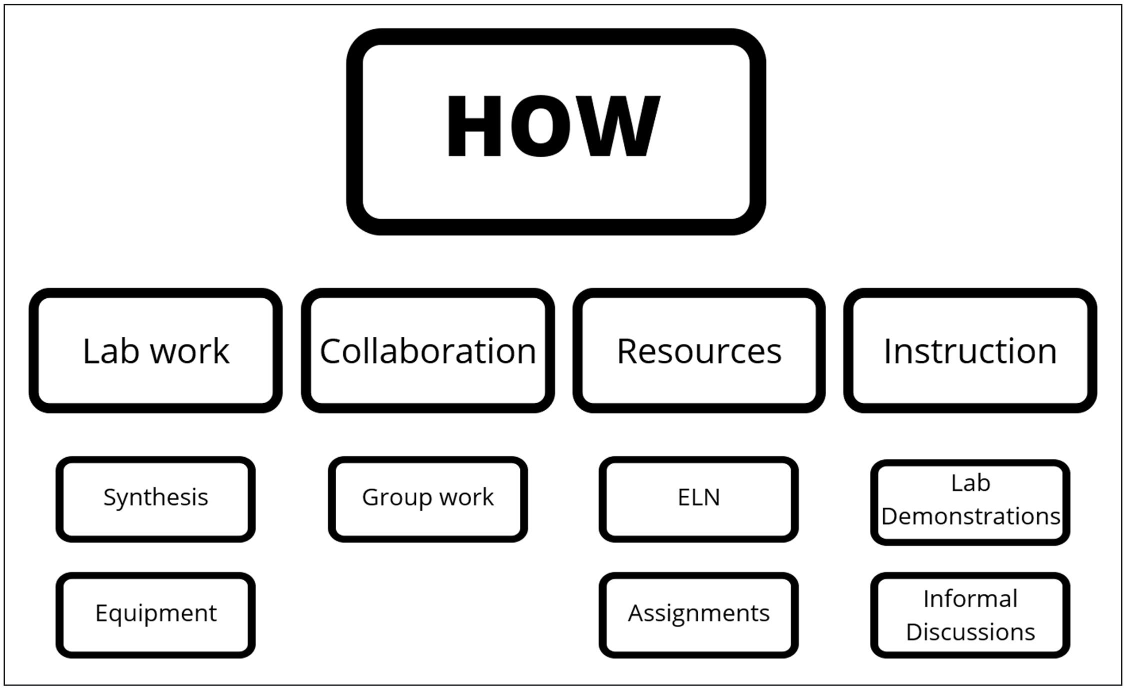

Figure 4 Student experiences of Breaking Good facilitating their learning.

experimental work was visiting these facilities where they learnt about nuclear mass resonance (NMR), mass spectroscopy (MS), and high-performance liquid chromatography (HPLC) instruments, and used them to analyse their own compounds and to confirm the structure of their final product:

> *"Just to make sure that we synthesized the correct product. It was really rewarding seeing that all of our carbon NMR and hydrogen NMR and everything else matched up with what we were expecting for the molecule" (S6).*

Students also indicated that the collaborative nature of the lab was an important facilitator for learning and overcoming challenges faced during their lab work. Students expressed enjoyment in working within a team and the advantages of sharing knowledge and developing a joint appreciation of the different steps of the synthesis and analysis. For example, one student wrote,

> *"Even within my own group, there were a lot of times when we had to discuss steps between each other because not everyone had the entire knowledge necessary to understand every step of the practice" (S10).*

Additional factors influencing how students learned included the use and review of learning resources, maintaining an Electronic Lab Notebook (ELN), and the creation of a science communication video as the final course assignment. Students used a variety of resources to learn about the goals and background of the Breaking Good project and the organic chemistry related to the synthetic procedures they conducted. These resources included an ELN and course webpage in which details of the synthetic procedures and background information on malaria and drug discovery were provided. Additionally, short videos featuring interviews with open source drug discovery practitioners were specifically created for students, and they were encouraged to visit the Breaking Good webpage. Some students also indicated that they conducted their own internet searches to learn more about malaria, drug discovery, and organic chemistry.

Much of the independent research conducted by students centred around a final assignment in which they were asked to prepare 5-minute videos explaining one aspect of the lab to final-year high school students. Additionally, while writing their own lab notebook, students were required to document all their activities in the lab and to answer a set of guiding and background questions. These exercises served to facilitate independent learning, as described by one student:

> *"There's a lot of other elements which weren't directly talked about, we were working on through either video or through the questions in our lab notebooks. Which, even though, it wasn't being specifically taught, it was really good because it forced you to have a look at stuff. Which is what*

you want to do as well, you want to have as much knowledge about what's going on as possible" (S1).

Finally, student learning was found to be strongly influenced by their student-teacher relationship with their lab instructors. Both students and lab instructors discussed the role that informal conversation plays in student inquiry about the process and context of the lab and in expanding their understanding and learning:

"I think the biggest resource I ended up using was actually my lab demonstrator. So, I actually asked him a lot of questions about what we were doing" (S3); and

"So, I guess, a main part of my role would be to supervise and teach the physical lab components which involves following whatever instructions they're given. But also making sure that they understand what's going on, both what they're actually doing in the labs […] but then beyond that, to understand how what they're doing on that one day sort of fits into the broader context of the project, and how that project fits into scientific contributions as a whole […] because I think it's a bit easier to explain these face to face because you can have a better discussion in the labs" (I2).

Observations of the labs confirmed this notion, with conversations recorded between students and lab instructors that covered topics such as lab procedures, the drug discovery process, and biological screening in addition to the chemical reactions undertaken and lab-related trouble shooting. Notably, the majority of lab conversations related to the chemistry and laboratory side of things, with little emphasis on the Breaking Good project and OSM, as described by one of the lab instructors:

"The focus is mainly they come into the lab, start doing the experiment, and get their compound. So, the time is quite limited to talk about anything else with them" (I4).

Students gave a similar response when asked if they discussed Breaking Good with project instructors:

"Oh, no, not too much. Most of the questions that I asked him and that we conversed about were more related to the science side of things" (S3).

WHAT ARE STUDENTS LEARNING? STUDENTS' DIVERSE LEARNING OUTCOMES

Engaging in the Breaking Good lab project resulted in several learning outcomes (the "what" of learning) among participating students. These were categorised into 1) knowledge, 2) skills, and 3) motivation, on the basis of the framework suggested by Phillips et al. (2018). An additional learning outcome identified through thematic analysis was 4) transfer. Transfer is the generalisation and transformation of scientific knowledge to daily life settings and a demonstrated understanding of complexity, power balances, and relationships between science and society, in relation to one's life (Mezirow 2000). The learning outcomes are summarised in ***Figure 5***.

One of the dominant learning outcomes from educational interventions is an elevation in student content knowledge. Indeed, participation in Breaking Good demonstrated an elevation in student knowledge of the drug discovery process and malaria, as these were the key topics discussed during lab participation and are a key focus of the research conducted. Additional forms of knowledge such as process knowledge and knowledge about the nature of science (NOS) also increased. Students stated their participation enabled them to "*…learn more about how chemists or scientists actually go about doing research*" and indicated this "*changed my understanding of how scientific research takes place*" (both S2). When demonstrating the knowledge they had gained, students noted their new view of the scientific process as a collaborative, timely effort, built on the knowledge of many previous studies and prone to trial and error. For example, one student said,

"I've learned more of the back end of drug discovery […] and how it seems to be a lot of trial and error to find the compounds which have the desired effect, or at least are on the right track for the desired effect. I've learned how science is a collaborative effort" (S9).

Hands-on synthesis has provided students with opportunities to increase their lab skills and to learn how to perform new procedures and lab techniques. These were indicated by all students interviewed in this study as the main learning outcomes of their involvement in Breaking Good. Students noted the new lab techniques learnt in addition to a new appreciation of their use in research contexts, as exemplified by the following quotes:

"So, the next time I step into a lab, and someone tells me to use a rotary evaporator or perform something like a vacuum filtration, I won't have to ask them what it is, I know myself and I'll be able to set up

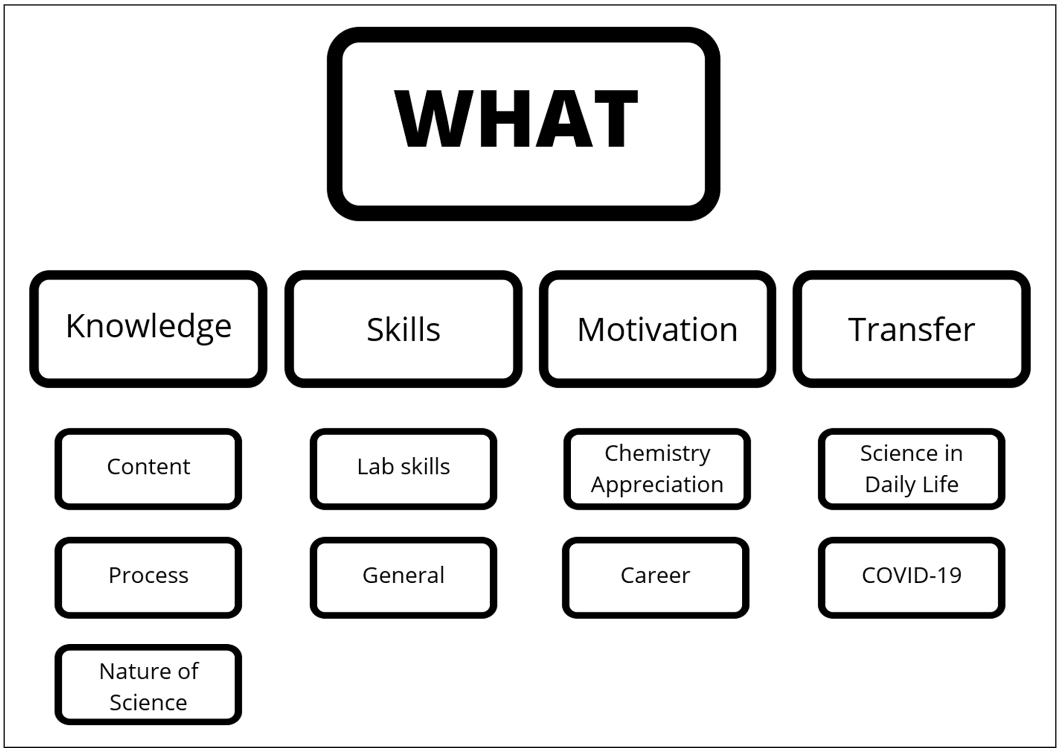

Figure 5 The diverse learning outcomes for students.

whatever I need to do myself. So yeah, I think the laboratory skills I learned this semester and in the project are probably going to be the biggest asset in the immediate future" (S3); and

"We had to use it [TLC] so many times to prove, what we're making this correct, which is so important, like you don't understand, how important it is until you realise that you need to make sure that what you're doing is correct. Because a lot of people could be dependent on what you're doing" (S7).

In addition to laboratory-based skills, students reported increased self-confidence and skills gain in areas including science communication, problem solving, and teamwork.

The knowledge and skills developed, coupled with increased student interest in drug discovery owing to the "why" and "how" described above, prompted a new understanding of chemistry, and motivated students to continue to engage with chemistry in the future. Students indicated the lab experience helped them see the broader scope and greater possibilities of a chemistry career:

"I feel like it gave me an idea of what chemistry research could be. And if I was to go in the chemistry field, what I could be possibly doing. So, it helped me get an insight into what future career paths could be for me in the future." (S7).

As portrayed by a lab instructor, this outcome was indeed one of the goals of the SSP labs:

"[The course] is like a taste of what the next step of their career would be. So, if they continue on from third year to honours research. I think it's a good way of testing their ability to adjust to those things" (I1).

As described above, an additional learning outcome identified in this study was transfer, the generalisation of scientific knowledge and skills to day-to-day context. Students described how the science they had learnt in textbooks and lectures came to life through the lab experience and the new connections they made between theory and practice. For example, one student noted,

"I actually saw the theory come to life in a way [...] And I think it was really good for me to make those links because I could actually apply my knowledge and not just like write it down in a test. It was actually going somewhere, which was really, really satisfying" (S3).

Students indicated that participation in the lab encouraged them to think about science in its broader context and consider how the scientific developments we all use today, were developed. This was emphasised mostly in the context of drug and pharmaceutical development rather than a general contextualisation of science in society. In one example, a student said,

> *"It's given me a lot more appreciation for the amount of time it takes to develop drugs and to put them on the market and the amount of people it takes to make something successful. In the future, I will have deeper appreciation of a lot of the things that we kind of take for granted at the pharmacy" (S10).*

Transfer also occurred in the specific context of recent world events, namely the COVID-19 pandemic and the push towards finding effective medications and vaccine development. Students indicated that participation in the lab served as an eye opener into processes linked to vaccine development:

> *"It [Breaking Good lab] really ties into COVID. Because generally, I believe, vaccine development takes about 15 years. But they're finding promising vaccines within the span of one year. And I think that's because scientists are cooperating from everywhere. They're all sharing their results, no one's being selfish. [...] This just goes to show the power that we could have if we all collaborated together on everything" (S6).*

DISCUSSION

This study examines student learning processes and outcomes from participation in Breaking Good undergraduate labs. It explores the why, how and what of laboratory learning through student participation in a citizen science project centered on the discovery of new medicines for diseases with low market incentives. Our findings reveal a dynamic learning setting enabled by many variables that jointly shape student learning. These include the unique learning environment established within Breaking Good labs as a hands-on, authentic, and novel science experience that advanced student knowledge in chemistry, scientific process, and NOS. Students developed laboratory skills and demonstrated an ability to transfer the disciplinary content, knowledge, and skills to a real-life environment.

Taken together, these findings point to the clear and innumerable advantages of incorporating citizen science in higher education, creating added value relative to traditional learning. This was exemplified by the increased motivation of students to participate in the lab and a deeper understanding of the purpose and process of chemistry research. Of special interest were the three key outcomes, which go beyond traditional content gains, and are increasingly seen as important qualities for university graduates (The University of Sydney 2020):

1. increasing student enjoyment and interest in science and future STEM-based careers;
2. connecting students to science in relation to their daily life, and recognizing science as more than a profession or discipline, but as a lens for lifelong decision making; and
3. exposing future scientists to science communication, public engagement, and open science methodologies as alternative research fields or methods.

These findings complement previous studies in the field of CURE that have found student participation to increase scientific skills and confidence, content knowledge, and the ability to work independently (Dolan 2016; Sorensen et al. 2018).

LEARNING THAT DID NOT TAKE PLACE

While it is rewarding to consider students learning outcomes and discuss what was learned, it is equally important to consider some of the things that students did not learn. Citizen science is emerging as an efficient instrument for science education and has been suggested as a tool to promote meaningful and broad learning outcomes, to sustain active citizenship, and to increase awareness and relatedness to science (Roche et al. 2020; Turrini et al. 2018). Because Breaking Good is centered on drug discovery for diseases with low market incentives, often endemic to countries where access to medicines may be compromised, it serves as an ideal setting to promote a greater understanding of equity issues in science and of accessibility of medication to people around the world, and a deeper NOS appreciation. Indeed, students recall the Breaking Good context and in particular their involvement in malaria research as a motivational factor (part of the "why") for their participation in the lab. Interestingly, student responses indicated that this did not broadly transfer to a deeper understanding of equity and access to science, nor to the important role of society and culture in science development and acceptance.

On reflection, we found that what students did not learn was in accordance with the resources provided and used by students and with the views and conversations observed between lab instructors and students. Although a wealth of information about malaria, chemistry, and lab techniques were provided and discussed, open drug discovery and accessibility to medicines for people around the world featured to a lesser extent. This finding further exemplifies the significant role lab instructors, and teachers more broadly, have on the learning outcomes of their students.

Lorke et al. (2019) discuss the important role facilitators of citizen science projects have in subsequent learning outcomes. They specify, "To achieve the project goals, facilitators must have a sound understanding of the nature of the citizen science project, the expected outcomes and the range of roles for participants in the project" (p. 17). In other words, to achieve desired project goals and learning outcomes, project facilitators (in our case lab instructors) should have a broad understanding of the project background, context, and directions. Furthermore, as discussed by Hansson and Leden (2016), topics related to the NOS, such as social dimensions of science, should be taught explicitly while making direct connections with relevant science content and laboratory work. Ultimately, these two principals were not demonstrated in the lab, suggesting part of the "why" was missing from student experience.

A number of caveats may have influenced the results and interpretations of this study as presented above. First the small sample of students participating in this analysis and the collection of data from one cohort limits the generalisability of findings and excludes perspectives of students who did not chose to participate in this study. Furthermore, while the use of qualitative data provides data richness and depth, a larger student cohort would have enabled the use of comparative quantitative methods.

This study was also impacted by the COVID-19 pandemic, during which uncertainty about whether the course would run led to some late-stage adjustments and less demonstrator training than in previous iterations. Social distancing requirements limited laboratory class sizes and prevented some of the face-to-face interactions.

CONCLUSIONS

Research is deeply embedded within the culture and mission of universities as places devoted to the advancement of knowledge, theories, and the technologies that consequently advance the future of our world. Training the next generation of researchers necessitates academics work closely with graduate students in research contexts but also means that some research opportunities are open to undergraduate students. Our study supports the idea that it is therefore a natural progression to embed research perspectives in the teaching of undergraduate courses, and that this can be readily achieved through citizen science participation. The involvement of undergraduate students as a previously untapped resource has considerable potential to expedite and democratise scientific discovery through the attainment of high-level data on previously un- or underexplored areas, as discussed by Heigl and Zaller (2014) and Ryan et al. (2018) and as exemplified in Breaking Good.

Beyond the benefits for the advancement of science, the expansion of citizen science into higher education teaching provides students with an enriched learning experience and increased learning outcomes, as demonstrated here and highlighted by Ryan et al. (2018). Our study investigated student learning processes through their participation in lab-based citizen science and highlights three aspects of the students learning trajectories—why, how, and what students learn. Although "how" and "what" are adequately addressed in the literature (e.g., Jennett et al. 2016; Kloetzer et al. 2021; Phillips et al. 2018b), we believe that it is the value of the "why", provided by citizen science contexts, that is transformative for student learning. The novel approach to teaching, which encompassed real-world context and authentic research, served as a powerful motivator for students, increasing their learning outcomes and appreciation of science. We therefore call for the expanded use of citizen science in education contexts, and particularly as part of university level courses. Universities are ideally placed to centre why students learn by expanding the scope of citizen science to new fields and settings.

DATA ACCESSIBILITY STATEMENT

The qualitative datasets generated in this study have not been made available owing to constraints of the ethical approval.

SUPPLEMENTARY FILE

The supplementary file for this manuscript can be found as follows:

- **Supplemental File 1.** Part A: Lab instructor interview protocol; Part B: SSP student interview protocol. DOI: *https://doi.org/10.5334/cstp.431.s1*

ETHICS AND CONSENT

This research was approved by the University of Sydney Human Research Ethics Committee (HREC), Project #2020/064. Informed consent has been obtained from all participants.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Both YNG and AM conceived the presented study, developed the theory, and led the writing of the manuscript. AM instigated and developed the SSP laboratory program. YNG conducted interviews and observations, analysed the data, and developed the presented frameworks. AM verified data analysis and framework construction.

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