The impact of open and reproducible scholarship on students' scientific literacy, engagement, and attitudes towards science: A review and synthesis of the evidence

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Funding: M.S. is supported by a Baily Thomas Grant, T.G-M. is supported by a UKRI/ESRC rapid call grant, K.M-S by Health Research Board Applying Research into Policy and Practice Fellowship, and B.J.I by a Northern Ireland Department for the Economy Research Studentship.

The impact of open and reproducible scholarship on students' scientific literacy, engagement, and attitudes towards science: A review and synthesis of the evidence

Abstract

In recent years, the scientific community has called for improvements in the credibility, robustness, and reproducibility of research, characterized by higher standards of scientific evidence, increased interest in open practices, and promotion of transparency. While progress has been positive, there is a lack of consideration about how this approach can be embedded into undergraduate and postgraduate research training. Currently, the impact of integrating an open and reproducible approach into the curriculum on *student outcomes* is not well articulated in the literature. Therefore, in this paper, we provide the first comprehensive review of how integrating open and reproducible scholarship into teaching and learning may impact students, using a large-scale, collaborative, team-science approach. Our review highlighted how embedding open and reproducible scholarship may impact: (1) students' *scientific literacies* (i.e., students' understanding of open research, consumption of science, and the development of transferable skills); (2) *student engagement* (i.e., motivation and engagement with learning, collaboration, and engagement in open research), and (3) students' *attitudes towards science* (i.e., trust in science and confidence in research findings). Our review also identified a need for more robust and rigorous methods within evaluations of teaching practice. We discuss implications for teaching and learning scholarship in this area.

Keywords: Higher Education; open research; open scholarship; open science; pedagogy; reproducibility; teaching

The impact of open and reproducible scholarship on students' scientific literacy, engagement, and attitudes towards science: A review and synthesis of the evidence

In response to concerns surrounding the credibility, robustness, and transparency of research, there's a noticeable acceleration in the adoption of open and reproducible scholarship tools (Azevedo et al., 2022). Open scholarship broadly refers to the belief that research should be transparent, rigorous, reproducible, replicable, accumulative, and inclusive (Parsons et al., 2022). Many practices have been developed to facilitate these goals, such as study pre-registration and Registered Reports (e.g., Chambers & Tzavella, 2022; Lindsay et al., 2016; Nosek et al., 2015), open materials, code, and/or data (Houtkoop et al., 2018), open access publishing (Nosek & Bar-Anan, 2012), and a focus on replication studies (Open Science Collaboration, 2015; Tierney et al., 2020, 2021). The usefulness of such tools is not confined to the social sciences, and it is important to note that they have also been considered across other disciplines (e.g., animal behavior, Farrar et al., 2020, 2022; cancer biology, Errington et al., 2021; economics, Camerer et al., 2016). While the discussions surrounding openness and reproducibility have led to promising and productive changes in research culture (e.g., Baum et al., 2022; Munafò et al., 2022; Stewart et al., 2022), there remains progress to be made (see Devezer et al., 2021; Ledgerwood et al., 2022; Whitaker & Guest, 2020). Specifically, there is an urgent, ongoing need to embed these principles into teaching, learning, training, and pedagogy (Azevedo et al., 2022). Indeed, if open and reproducible scholarship is not explicitly embedded into undergraduate or postgraduate teaching and learning, students will not be well equipped with the knowledge and skills to continue advancing the goals of open and reproducible scholarship and to contribute to sustained culture change (Azevedo et al., 2019; Pownall et al., 2021a). It is, therefore, crucial that the pedagogical aspect of open and reproducible scholarship is at the centre of discussions.

Many scholars have made the 'moral case' for adopting open scholarship tools, noting how open scholarship is necessary for the accessibility, inclusivity, robustness, and advancement of research (e.g., Chambers, 2019; Hales et al., 2019; Vazire, 2018; Willinsky, 2006). However, the focus of existing work has primarily made the case for why fully trained *researchers* should integrate open and reproducible tools into their research pipeline, focusing on the impact *for* researchers and knowledge production, rather than exploring how the teaching and learning of open and reproducible research practices may impact *students*. While there have been some useful discussions surrounding the need for open scholarship in teaching and learning contexts in recent literature (e.g., Anglin & Edlund, 2020; Button, 2018), a comprehensive summary of the *empirical* evidence is lacking. Based on this review, we argue that taking an open and reproducible scholarship approach to teaching and learning may not only be 'good for science' but also beneficial to students.

Aim

The aim of this paper is to review and synthesize evidence investigating the impact of embedding open and reproducible scholarship on student outcomes. The outcomes we are interested in are students': (1) scientific literacy, (2) engagement, and (3) attitudes towards research. These themes represent three fundamental aspects of the student experience that capture both students' development of skills *during* teaching and learning and down-stream consequences following their research training.

Literature Search Strategy

This paper presents a literature review and synthesis of the evidence relating to the impact of embedding open and reproducible scholarship on student outcomes. We opted to conduct a literature review in order to: a) include the evidence that exists in non-traditional spaces (e.g., gray literature, including unpublished student evaluations and online talks); b) ensure that the full breadth of definitions of open and reproducible scholarship were captured;

and c) rigorously evaluate the evidence in this area. This review includes studies involving undergraduate and postgraduate students, in all subject areas, on a global level.

Establishing the Search Strategy

To stay impartial and to capture a wide evidence base, our review and synthesis of the evidence was guided by the following predetermined research question: *What are the impacts of incorporating open and reproducible principles into teaching upon student students' scientific literacies, student engagement, and attitudes towards science?* To achieve this, we created an *a priori* search strategy, containing search terms, search places, and inclusion criteria. The search strategy was devised by a subset of the authorship team with expertise in literature reviews *(*see *CRedIT Statement;* https://osf.io/hg7nt/). This search strategy was informed by guidelines for best practice in non-intervention reviews, including NIRO (Topor et al., 2020) and SPIDER (see Table 1). The search included main academic platforms for formally published research (Web of Science, Scopus, EBSCOhost, Pubmed, Medline, Embase), preprint archives (PsyArXiv; ProQuest dissertations, Open Science Framework, EdArXiv, MetaArXiv), as well as additional academic resources for emerging and unpublished research (Education Resources Information Center [ERIC], Bielefeld Academic Search Engine, OpenGrey), the FORRT community, and Twitter. The search strategy in full, including search places, search terms, and results can be accessed here: https://osf.io/29qvh. The complete inclusion criteria were as follows:

1. The paper discusses open and reproducible scholarship in the context of Higher Education, including (but not limited to) undergraduate students, taught postgraduate students and/or research students (e.g., Masters and PhD by Research).
2. The paper specifically mentions the impact of open and/or reproducible science on student (undergraduate or postgraduate) outcomes.

Table 1. Outline of search strategy, as informed by SPIDER (Methley et al., 2014)

SPIDER category	Strategy in the present paper
Sample	University students; Higher Education; undergraduate
Phenomenon of interest	Replication; open science; open scholarship; open research; open practices; open principles; open pedagogy; preregistration; pre-registration; Registered Reports; "reproducib*"; reproducible; reproducible science; crowdsourcing; "*registr"
Design	Qualitative, quantitative, or mixed-methods
Evaluation	Attitudes OR student engagement OR perception OR outcomes
Research type	Qualitative & mixed-methods; experimental; observational

Search terms included: teaching; mentoring; pedagogy; open scholarship; open educational resources; replication; reproducibility; research repository; student projects; empirical dissertation; team science; data sharing; replication crisis; reproducibility crisis; Many Labs; Hagen Cumulative Science Project; questionable research practices; responsible conduct of research; detrimental ethical practice; educational practice; Collaborative Replications and Education Project (CREP); dissertation; College Teaching; Framework of Open Reproducible Research Training (FORRT); Project TIER; research transparency; service learning; credibility; preprints; registered reports; public understanding of science; science communication; epistemic trust; trust in science; attitudes toward science; open source materials; undergraduate preregistration assignment; scholarship of teaching and learning; Higher Education.

Literature Search

After devising and finalizing our search strategy (Table 1), a sub-team then ran a comprehensive search of the literature; the full protocol can be accessed here: https://osf.io/4jqbw/. The search was conducted from December 2021 - January 2022. This

search resulted in an initial selection of 866 identified papers. A second subteam then reviewed each paper against the two above inclusion criteria, categorized each paper as qualitative/quantitative/mixed methods, noted the student sample (undergraduate or postgraduate), and provided additional comments. Each paper was independently evaluated by two coders, who were blind to each other's decision, using separate tabs on a shared Google Sheet to facilitate collaboration. Coders were randomized to one of two coding sheets and randomization of authors to coding was achieved using author surnames. When a paper was deemed to fit the inclusion criteria, coders assigned it to the three thematic categories that formed our research question (*scientific literacies, student engagement,* or *attitudes towards science*). These categories were not mutually exclusive; that is, a paper could be assigned to more than one thematic category.

After coding was complete, entries that did not meet the inclusion criteria (N = 829) were removed. Interrater reliability was strong (κ = .915). Discrepancies between codes were discussed and resolved with the wider team, leading to a final set of 36 screened papers. The core writing team (see *CRediT statement*) then received a shared drive which contained all of the relevant screened papers, organized by three distinct categories: *scientific literacies, student engagement,* and *attitudes towards science.* Sub-categories were also identified (Table 2). The list of 36 papers were not used exhaustively and other relevant papers and gray literature were added iteratively to a shared drive, following wider review of the literature. This was primarily achieved using forward and backward citation searching of the relevant papers identified by the review, as well as wider searches in gray literature that were not covered by the review; for example, links shared on Twitter, the Project Teaching Integrity in Empirical Research (TIER) website, and the FORRT community. Papers identified by the systematic review process are indicated with an asterisk in the reference list. In the review, we identified broadly two different types of research, either a) research which considers the

integration of open and reproducible scholarship tools and practices, or b) research which evaluates the use of open educational resources. We now summarize the evidence across the three thematic categories, before discussing wider implications.

Table 2. Thematic categories and sub-categories identified by the literature review

Thematic category	Sub-categories identified by the literature review
Scientific literacies	Understanding of open research, students' consumption of science, development of transferable skills
Student engagement	Motivation and engagement with learning, collaboration and student involvement, engagement in open research behaviors
Student attitudes towards science	Students' trust in science, confidence in research findings

Impact of Open and Reproducible Scholarship on Scientific Literacies

Recently, there has been a heightened emphasis on 'scientific literacies' as a core competency for undergraduate and graduate education (OECD, 2006, 2017). Scientific literacy refers to the knowledge, skills, competencies, and attitudes related to both scientific culture and 'doing' science (for a review on how scientific knowledge has been conceptualized see OECD, 2017; Tang & Williams, 2019). In research-based subjects, this may include statistical competencies, understanding of research practices, and other practical research skills students develop throughout their studies. A concern for scientific literacies is becoming rapidly integrated within accreditation and policy in Higher Education across countries (e.g., in the UK, Hubbard, 2021; and in the US, APA, 2013, 2018). Therefore, it is necessary to reflect on how scientific literacy can be impacted by the adoption of open and reproducible scholarship practices in students' curriculum.

This represents the first thematic category that was highlighted by our review and guided by our research question. Scientific literacy, in context of the present paper, refers to competencies and skills taught to students during their program, which are generally related to the production and consumption of science and scientific knowledge. Previous work has investigated interventions to improve students' scientific literacy, for example, with initiatives such as inquiry-based learning projects with students (McCright, 2012) and hands-on science training for school-aged students (Wang et al., 2022), with positive outcomes. In this context, embedding open and reproducible approaches to research teaching and learning may also aid students' development of discipline-specific scientific literacy (Anglin & Edlund, 2020). Our review suggests three broad areas within students' scientific literacy that can be impacted by the implementation of open and reproducible scholarship: (1) students' understanding of open research, (2) students' consumption of science, and (3) the development of transferable skills. We now detail each of these in turn.

Students' Understanding of Open Research

Overall, our review showed evidence that explicitly embedding open scholarship tools, for example, study pre-registration (i.e., the process of creating a time-stamped account of study hypotheses, methods, and planned analyses before data analysis; Parsons et al., 2022), into coursework can help students to be more *literate* with the interpretation of statistical results. For example, Blincoe and Buchert (2020) found that undergraduate psychology students reported pre-registration to be a helpful planning tool because it allowed them to understand the value that null or non-significant findings have in research. As Blincoe and Buchert (2020) explain, pre-registering research with undergraduates can also serve to demonstrate to students how questionable research practices (QRPs; i.e., problematic practices that researchers engage in to improve the chances of gaining significant results; Parsons et al., 2022) can be reduced, especially with regards to recognising the difference

between *a priori* and *post-hoc* research decisions. Thus, incorporation of pre-registration in pedagogy can promote best practice in quantitative research and strengthen students' understanding of research findings which, in turn, promotes scientific literacies. There was also evidence in our review that implementing study pre-registration may help students develop their scientific literacies in other ways. For example, as Pownall (2020) argues, aligning the quantitative analyses more clearly with students' original research questions can increase the perceived usefulness of statistics. Similarly, introductory data science course focusing on the use of version control, open-source tools, and improved statistical conclusions has grown in popularity with students across diverse disciplines (Çetinkaya-Rundel & Ellison, 2021).

Our review also highlighted useful case-study examples of how embedding open and reproducible scholarship into teaching and learning can improve students' scientific literacies, with a focus on students' understanding of open research. For example, Toelch and Ostwald (2018) designed and evaluated a hands-on postgraduate course on integrating open and transparent research projects into students' local research projects. Over 60 hours in the course, students were introduced to the ethos of open research as well as practices including pre-registration, FAIR (Findability, Accessibility, Interoperability, and Reusability) data sharing, version control, and open access outputs. Half of the students enrolled on the course responded to an evaluation six months later, which found that students were generally positive about open scholarship and the hands-on research project element of the course. Further, 80% of the students agreed that using open practices would improve the quality of their own research. In this example, Toelch and Ostwald (2018) provide a useful case study of how learning open practices may confer advantages to students' scientific literacies when embedded across the curriculum.

There were useful case-studies of how embedding a concern for *replication*, as a second example of a commitment to open scholarship, may impact students' scientific literacies (e.g., see Janz, 2019). The Hagen Cumulative Science Project (Jekel et al., 2020), for example, was initiated as a systematic mechanism for German undergraduate students to conduct replication studies as part of course requirements of completing a research thesis project. In this project, students pre-register their projects, share their data and analysis code, and are encouraged to use open-source statistical software. While Jekel et al. (2020) did not directly evaluate students' learning outcomes, the authors noted that at the time of writing, more than 80 replication thesis projects had been conducted, suggesting that students had successfully learned about and used open practices to pass their thesis work. This represents the value of hand-on training which promotes scientific literacies. Similarly, Collaborative Open-science REsearch (CORE; Feldman., 2022) is a mass-replication-extension project in judgment and decision making and social psychology, with students from University of Hong Kong Department of Psychology and international early-career researchers. This project, which involves students conducting collaborative studies with hands-on support, has resulted in 20 peer-reviewed publications (e.g. see Brick et al., 2021; Chandrashekar et al., 2021; Ziano et al., 2021). In student evaluations of this project (Feldman, 2021), a student wrote "*I learned a lot about designs of experiments, adding extensions to them, as well as the impact of replications. It was fairly challenging, but the takeaways from this course were huge*". Therefore, beyond the clear career benefits of publishing peer-reviewed journal articles, students also developed their scientific literacies, including analyses and coding with reproducible open-source softwares (e.g. Jamovi and R), analyses and assessment of original articles (e.g. detecting errors, effect size and confidence intervals calculations), power analyses (e.g. using G*Power or R packages), and rigorous interpretation of results (e.g. not over-relying on *p*-values) during the process. In this case study, scientific literacies were not

directly measured quantitatively, but the product of this replication-extension project was generally well recognized for its high reproducibility, transparency, and rigor by the scientific community.

Furthermore, integration of replication and reproducibility studies can be a useful way of developing students' scientific literacies; Smith et al. (2021) integrated replication studies as part of academic training for twenty-four graduate students. In this initiative, students reproduced the results from instructor-selected high-impact papers in biostatistics using the original authors' raw data and reported statistical methods. Based on their experience, in an evaluation, students reported enhanced understanding of the research process and replication, more exposure to new statistical methods, and increased practice with scientific writing. Most of the students also reported an increase in their self-confidence with data analysis and provided positive comments regarding the overall experience. This is particularly encouraging, given the widespread prevalence of statistics anxiety among university students, particularly in disciplines such as psychology. The potential for this type of pedagogic approach to mitigate such anxieties and to build students' confidence in analyzing quantitative data merits further research. Challenges centered around access to data required for reproducing study results and the necessity to select published articles that did not require analytical techniques that were too advanced for students in the course. This demonstrated the value in replication as a pedagogic tool that enhances students' scientific literacies.

Beyond replication and reproducibility, there were other examples embedding open and reproducible scholarship into teaching and learning, through innovative, active-learning approaches to help students understand aspects of the research process (e.g., Pyott, 2021). For example, Sawchuk (2018) reported an evaluation of an active learning activity, whereby small groups of undergraduate students replicated a published study which investigated contents of age-specific birthday cards. Each group of students was asked to analyze a set of

15 different birthday cards and to share qualitative and quantitative findings with classmates before submitting a written discussion section on their results to the course instructor. This was a replication of a published study which used an identical analytical approach. As a result of this project, students developed a solid understanding and application of the course concepts. There was also some evidence that the influence of the exercise and its associated active learning activities persisted until the end of the term. A new element of this study that was not included in the study that the authors replicated was that some students did reference the activity and incorporate their findings on the take-home final exam. Further, the year-end course evaluations revealed that the course's active learning exercises made the class interesting and helped students better grasp course material. However, more formalized measures are needed to make a claim about the benefits of the exercise. A second example is Altunoglu (2017), who also emphasized how utilizing open-education learner management systems can improve student literacies, by making students "active participants in their own learning" (p. 96), which also highlights how open tools may increase active learning in teaching and learning contexts.

Furthermore, our review identified examples of larger-scale, collaborative approaches in supporting students' scientific literacies. For example, the Collaborative Replications and Education Project (CREP; Wagge et al., 2019) supports students in conducting a replication project, under the guidance of a supervisor and with oversight of the CREP team. Students gain experience of tools such as the Open Science Framework, an internal peer review process, preregistration, and open data and code. Students contribute their data to a meta-analysis which can, potentially, result in authorship on published papers. Thus, students receive authentic training in relevant research skills within a context that is analogous to the wider research ecosystem. Wagge et al. (2019) noted that more than 120 student groups had begun a project through CREP, demonstrating widespread interest in the value of replication-

based research training. In general, it is noted that involving students in fully realized research projects, even from the first undergraduate year, may lead to improvements in general research skills, increased interest in a science-focused degree, and course engagement (Stiemsma et al., 2020). This is aligned with the values of open and reproducible scholarship, because it promotes the principles of collaborative, transparent approaches to research (see IJzerman, 2019, for another example).

Open scholarship training can also benefit students' skill development. For example, Steinhardt's (2020) experience of teaching open practices for qualitative work suggested that the wider educational context may impact development of scientific literacies. In Steinhardt's (2020) case study, students generally used practices and skills when they were mandatory but did not go above and beyond requirements. It may be that when the educational system encourages students to be producers of knowledge and of learning, development of research skills such as open and transparent practices can be most successful. A note of caution comes from Sacco and Brown (2019) who found that an educational intervention to reduce acceptability of questionable research practices (QRPs) among postgraduate students was effective one week later, but that acceptance of QRPs had risen two months later (though not quite as high as pre-intervention levels). These authors note that repetition of such training might be needed to maintain scientific literacy. Thus, it may be that training in the use of open and transparent research practices should be repeated or maintained over the longer-term.

Students' Consumption of Science

In addition to students' scientific literacies in terms of how students *do* research themselves, *consumption* of science also forms an important part of scientific competencies. We conceptualize consumption of science as students' ability to consume, critically appraise, and evaluate research findings. Our review demonstrated that there is a plethora of peer-

reviewed articles in this area. Haas and Rouse (2022) recommend that students be introduced to the concept of correction in the scientific record, associated terminology, and taught how to identify and interpret correction notices, when encountered during a literature search. One of the key requirements of a reliable scientific record is that publishers issue corrections whenever substantive errors in published research are identified. Complicating this picture is the variety of terms used to refer to corrections, including errata, corrigenda, and retractions. As part of this process, it is essential that students be taught that corrections, particularly non-retraction corrections, are not all the result of research fraud or fabrication. Understanding the role of corrections provides necessary knowledge regarding the academic publishing process, while also introducing concepts such as fallibility and responsibility for ensuring the accuracy and completeness of the scientific record.

Moreover, there were case studies in our review in which students were encouraged to understand the *process* of research itself. For example, Marshall and Underwood (2019) describe a project that was a component of an upper-level undergraduate economics writing-in-the-discipline course and that can be adapted in different undergraduate economics courses. The objective was for students to develop an understanding of how economists conduct applied empirical research. One of the main desired learning outcomes of this project was that students should demonstrate an understanding of the necessary components of a well-written empirical research paper and the economics discipline's formatting and style conventions. They should also be able to interpret existing knowledge. There should be a strong link between academic writing and subject knowledge, which forms the pedagogical rationale for Marshall and Underwood's (2019) writing course. They used a number of tools and programs for statistical computing, word processing and providing feedback, and assignment submission and return, with reproducibility in mind. Each of these tools aimed to help students connect their discipline-specific writing skills with applied empirical research.

The authors also discuss ideas such as peer-review that can be added in future projects like this one.

Drawing on their experience from methods courses taught to undergraduate and graduate students, Frank and Saxe (2012) argue that students should replicate recent findings as part of their training in experimental methods. In their own courses, the authors found that replicating cutting-edge results is exciting and fun for students; it gives them the opportunity to make real contributions to science, and provides understanding of the scientific process, the importance of study reporting standards, and the value of transparency and openness. One of the benefits of doing replications to students is that they learn much from carefully reading others' papers '*with the eye of a replicator, not just a reader*'. Planning replications requires focusing on the details of methods and analyses used in the previous studies. The authors found many additional practical and cultural benefits of student-led replications. For example, reading with the goal to replicate helps students appreciate transparent and complete scientific reports. Experiencing the frustrations of trying to sort out others' incomplete reports of the study is the best argument for writing better, transparent protocols yourself in the future and this helps to learn the value of open sharing. The paper ends with acknowledging that in-class replications are not a panacea, but these obstacles should not prevent us from beginning somewhere, and they suggest that the beginning should be in the classroom.

Development of Transferable Skills

There was also evidence to suggest that open and reproducible scholarship can impact development of certain transferable skills for students. The advancement of students' scientific literacy directly promotes the development of closely related skills transferable into contexts outside of academia. The ability to work with quantitative data, draw accurate conclusions and understand the limits of inferential methods is a widely sought-after skill-set

in the industry (Çetinkaya-Rundel & Ellison, 2021). By engaging in open scholarship, students can develop the ability to work as part of a team - whether in the area of collaborative coding, problem-solving, or co-production of knowledge (Button et al., 2020; Çetinkaya-Rundel & Ellison, 2021; Marwick et al., 2020; Stiemsma et al., 2020) - while also fostering a sense of independence and agency of their own learning process (Baran & AlZoubi, 2020; Ryan, 2020). Furthermore, students who receive training in reproducible scholarship may also be better equipped with public science communication, because they have received training in communicating research findings in a transparent and accessible manner (Baran & AlZoubi, 2020; Kathawalla et al., 2021).

Our review also highlighted that students can benefit from the teaching skills and the understanding of how education in general is structured (Andone et al., 2020; Ryan, 2020). For example, this can be relevant for those directing themselves to education-related careers or can be transferred to any training or coaching context in other career fields. Andone et al. (2020) in particular charge a small number of students with creating open educational resources as a way to enrich a STEM undergraduate and postgraduate programmes and, at the same time, as an assessment from which students gain knowledge on best practices in education content creation. The qualitative data gathered from Andone et al.'s participating students demonstrated that 94% of them found the practice useful and applicable to a number of course elements (e.g., for theoretical knowledge transmission, independent knowledge evaluation and study).

Scientific literacy skills can be valuable in careers where the communication of scientific findings to stakeholders with non-science backgrounds is imperative. For example, Baran and AlZoubi (2020) conducted semi-structured interviews that explored students' perspectives of open pedagogy. These interviews demonstrated that students found learning about open scholarship benefited their ability to critically analyze science as well as

improved their understanding of broader ethical issues such as trust and integrity. One of the most important potential benefits of open scholarship education is the development of reproducible coding and data analytical skills, which may be helpful for future careers. Marwick et al. (2020) argued that adopting reproducible routines may help students in their future career by developing the habit of creating code and data that are transparent and organized for easy access of others.

Similarly, Çetinkaya-Rundel and Ellison (2021) presented a case study on the benefits of a data science course (which is different from typical statistics courses, as it emphasizes open source/data and reproducibility) and argued that the course can help students in developing reproducibility routines, specifically version control and coding collaboration skills with Git and Github (through working with other students on assignments), which are transferable skill sets desired by future employers. Furthermore, apart from reproducibility, the course also taught students assessment of robust and replicable analytical methods, inference, drawing rigorous conclusions based on data (e.g., not over-relying on significance of *p*-values), and communication of results. Çetinkaya-Rundel and Ellison (2021) also mentioned that the course satisfies statistics requirements for students in a wide range of different disciplines and students were allowed to work on any dataset for their final project. In addition, Andone et al. (2020) find that students' participation in open educational resource creation enriches their digital lifelong learning abilities. Their study showed that a high majority of the participating students claimed they had to learn new technologies in order to accomplish the task of open educational resource creation, and the tools used varied, due to the creative nature of the task (see also Necheukhina et al., 2017).

However, there is also evidence demonstrating *little* impact on student outcomes, in formal evaluations of students' future research behavior. For example, Nurse and Staiger (2019) evaluated the impact of a service-learning activity where students analyze real-world

data on behalf of nonprofit organizations. An evaluation showed that this exercise failed to find evidence for an impact on students' attitudes, confidence, or planned research behaviors over and above the effect of simply attending lectures about reproducibility. However, qualitative comments indicated that students who participated in the service-learning activity were better able to describe the different elements a journal might require for reproducibility (e.g., command files and a data appendix) in comparison to a control group, suggesting an increase in scientific literacy relating to reproducible data analysis.

Finally, our review demonstrated the value in positioning students as co-creators, or co-producers, in a research context, which aims to strengthen students' 'hands on' research training and encourage students to be active researchers in their curriculum. For example, Ryan (2020) showed how hands-on research training can improve students' sense of ownership and independent thinking with their research practices (see also Button et al., 2020). This theme was also discussed by Baran and AlZoubi (2020), who developed a qualitative analysis of student reflections following an open education resource-based module. The authors demonstrated that students felt a strong sense of agency and ownership of their own learning and knowledge (Baran & AlZoubi, 2020). Similarly, as discussed by Button et al. (2020), restructuring typical undergraduate research projects to be larger, better powered, collaborative efforts of a consortium of students not only taught students about the principles of high-quality transparent research but also allowed students to benefit from joining a "knowledge creating community" (p. 85). A similar approach was described by Stiemsma et al. (2020), who developed a 'Students as Scholars Program'. In turn, this encouraged the development of highly sought-after transferable skills such as teamwork, problem-solving and co-production of knowledge (Button et al., 2020). These skills are argued by the authors to be not only desirable in the modern workforce but also deemed necessary to meet the challenges facing the global community today.

Overall, from this we can conclude that there is a good body of evidence to suggest that integrating an open and reproducible scholarship approach may confer advantages to students' scientific literacies. The majority of the research considered how students' understanding and competencies, including research competencies and statistics literacies, can be bolstered by open and reproducible approaches. Importantly, and perhaps most unexpectedly, our review also demonstrates how embedding open and reproducible scholarship can impact non-discipline-specific skills, including transferable skills such as writing, teamworking, and problem-solving. Therefore, this broadly suggests that, while there were some case studies which found little effect of integrating an open approach, open scholarship in teaching and learning contexts can be useful for students' skill development. This includes both research-specific skills, such as statistical understanding and knowledge about open science, as well as more transferable skills that may be useful in employability contexts.

Impact of Open and Reproducible Scholarship on Student Engagement

The process of acquiring research competencies and improving scientific literacies would not be impossible without students' *engagement* with teaching and learning about research. Student engagement is thus an important, yet often-overlooked, facet of the student experience in the context of research training. A concern for student engagement is often undervalued across Higher Education, due to an inherent focus on academic achievement as the sole measure of 'student success' (e.g., Kahu, 2013). Therefore, the student engagement literature is smaller and less developed than the research literature investigating competencies and literacies. Further, student engagement is also a complex term that differs between subdisciplines, but it broadly infers ways in which students are involved with and enjoy their academic studies. Thus, the term is related to subjective outcomes (e.g., student satisfaction and wellbeing) as well as objective measures (e.g., retention, academic success; see Kahu,

2013). Our review highlighted many examples of how open and reproducible scholarship can impact student engagement, including a focus on (1) students' motivation and engagement with their learning, (2) the value of collaborative, student-centered approaches to open scholarship teaching, and (3) the impact on students' engagement in future open research behaviors. These three facets of engagement are largely aligned with Groccia's (2018) model of student engagement, which notes how there are three distinct areas of engagement: affective (e.g., interest, enjoyment, motivation), cognitive (e.g., focus, concentration, reflection), and behavioral (e.g., effort, persistence, dedication) engagement. We now synthesize the evidence across these perspectives, with a focus on facets of student engagement.

Motivation and Engagement with Learning

Our review demonstrated evidence from the open scholarship literature that the embedding of open and reproducible teaching and learning can not only be useful to scientific skills, competencies, and literacies, but also for wider engagement, motivation, and satisfaction with teaching and learning. This can be achieved through the integration of open scholarship tools. For example, Frank and Saxe (2012) make a compelling case for the notion that replication of studies with students can be an opportunity for exciting 'hands on' research training, which gives students the chance to contribute to scientific research and provides lessons about the scientific process. As the authors proposed, "the best way to motivate students to learn experimental methods is to use the same logic that motivates working scientists" (p. 601). The PsyTeachR project at the University of Glasgow (see McAleer, 2021) has embedded open software R and RStudio to help student learn reproducible and robust methods with real datasets; in an evaluation, students found the experience of learning R "*very exciting and going through it with the teaching assistant was extremely helpful.*" (Barr, 2016). Similarly, Button et al. (2020) reported that students "greatly valued

participating in a consortium-based model for training students in conducting reproducible research projects, particularly having access to a meaningfully large data-set; the opportunity to network with academics, students, and researchers from other universities; the sharing of ideas and knowledge; and contributing to pre-registration" (p. 86). This further evidences the engagement value of adopting such an approach with students.

Another example of tools and practices aligned with open and reproducible scholarship is Davis and Parmenter's (2021) embedding of a participatory action research (PAR) approach within pedagogy. This approach centers around working collaboratively with students to co-create research and understanding. Davis and Parmenter (2021) used questionnaire, diary and semi-structured interviews, with a small group of students (N = 7) and staff (N = 2) and reported that the PAR approach makes students feel safe and accepted in a community, where they can freely express themselves. In addition, participants report changing their perceptions of education and their expectations and goals for their own educational path (i.e., considering further education, gaining interest in more subjects and perspectives, feeling more credible and capable of contributing to the development of knowledge). This confidence and feelings that the students can contribute to knowledge both in education and in their future professional fields, can build in learners an approach of inquiring and questioning knowledge more effectively, despite their socio-economic background.

Similarly, students' affective engagement is also promoted through use of open educational resources. For example, Afolabi (2017) showed how such resources are seen as an advantage by students, who particularly agreed with statements such as they "makes learning more meaningful" and they are "a positive innovation" (p. 117). Werth and Williams (2021) also qualitatively investigated the effect of pedagogy informed by open educational resources on students' motivation and engagement with students' learning. The involvement

of students in co-creating the educational resource that would be available to their peers in future years was shown to increase student motivation and confidence with the content. Likewise, Paviotti et al. (2020) report high student enjoyment and satisfaction (N = 24) regarding the design of a tourism course delivered through the use of open education principles.

Another example highlighted by our review is Lin (2019), who investigated student perceptions of open educational materials compared to traditional textbooks within an introductory education course. Survey and focus group data revealed that the majority of students (survey respondents 84.7%; focus group members 86.2%) viewed the open materials favorably, highlighting dynamic and plentiful materials beyond what would be typically contained in a textbook, the ability to access the materials anywhere digitally, and the cost saving factor for their education. Within the focus groups, students emphasized that they were able to access material with greater ease, which enhanced engagement. Sanchez et al. (2021) also investigated students' perception of open educational resources, over the course of one year, on a criminal justice course. Qualitative student feedback showed two emerging topics: (1) feelings of relief and (2) perception of accessibility. Students reported feeling relief mainly due to the high financial costs and limited availability of resources in North American institutions. In addition, the results reported that the majority of students (80%) reported perceptions of increased accessibility of the resources, allowing them to study, practice, annotate and transport resources more efficiently. Accessibility was also related to allowing visually impaired students to interact with the digital resources more efficiently than with traditional printed books. Similarly, Watson et al. (2017) examined use of a free, open-access online textbook and showed that students highly valued the quality, features, and cost of the online textbook. Further, by integrating open educational resources in teaching and learning, this resulted in clearly articulated learning outcomes, a fully realized structure in the

course learning management system, and improvements in classroom practice. Students thus clearly benefit from the use of open educational materials.

It is important to shed some light into how open and reproducible scholarship may help overcome certain barriers to students' engagement, such as those experienced by marginalized or under-represented students. For example, Bangera and Brownell (2014) describe a 'course-based undergraduate research experience' (CURE) initiative, which aims to provide under-represented students, women, and those of low socio-economic status, with 'hands on' science training. The authors describe how students who are under-represented and are first-generation university students face barriers including awareness of cultural scientific norms, access to opportunities, and perceived barriers to interactions with faculty members. The CURE initiative uses course-based undergraduate research experience to prompt engagement with science among under-represented students and, by extension, allows the exploration of "questions with unknown answers to expose students to the process of scientific discovery" (p.604). Thus, open scholarship practices can have an important role to play in promoting wider engagement with science among students.

Similarly, the accessibility agenda can also be promoted by encouraging and supporting students to curate and prepare learning tools that benefit other students. Bloom (2019) randomly allocated classes in an introductory English course to complete a traditional assignment where students wrote an essay, or an open assignment where students remixed open educational resources into a learning tool that can benefit others. When Bloom (2019) compared the two groups on their performance in an end-of-module quiz and argumentative essay, there was no evidence for differences between the two groups; however, the author argued curating open educational resources allows students to share material to benefit others, while providing a meaningful educational experience for themselves.

Indeed, knowledge of the practicalities of conducting open scholarship can also positively impact students' attitudes towards important issues, such as copyright law and integrity. For example, Hare et al. (2020) created a curriculum centered around the production of an open educational resource for post-graduate students in the field of education (see also Al Abri & Dabbagh, 2019, for a similar intervention). Beyond teaching about open access pedagogy, the curriculum aimed to improve knowledge surrounding topics such as information privilege, intellectual property, access, and copyright which in themselves are relevant for many careers both within and beyond research. Importantly, the students were challenged to engage with discussions about the power structures underlying knowledge creation and dissemination, for example. Similarly, Baran and AlZoubi (2020) found students became aware of differences in language-based privileges in terms of knowledge access with students becoming conscious of ensuring the open educational resources they curated were accessible to individuals with English as a second language.

Collaboration and Student Involvement

Our review also demonstrated how students' attention, motivation, and reflection can be enhanced by open scholarship via adopting more collaborative approaches to student research. For example, Button et al. (2020) found that embedding a *team science* approach to teaching meant that students network with peers and researchers at other institutions, have exposure to better practices, and thus feel less isolated and more valued as part of a team. Clark et al (2020) also describe how students benefit from working with peers; the authors created a Peer Research Consultant programme, which trained students in research support, and found that students enjoyed seeking research assistance from peers over librarians. As Button et al. (2020) explained, collaborative, team-based approaches to research with students may improve students' comfort and creativity with research processes (see also Button, 2018, Pennington et al., 2022). More detail on the team science approach which

elicited these positive attitudes towards participating in team science, and the knowledge exchange that results from it, is described in Button et al. (2020). Similarly, in another example, Poronnik and Moni (2006) used the team science approach to improve undergraduate students' science communication skills via the task of collaboratively writing opinion editorials, followed by an open and transparent peer review process. Poronnik and Moni (2006) evaluated this approach and found that students generally appreciated the experience and found it cognitively challenging (80%) yet valuable (70%); so, overall, the team approach was considered as a rewarding learning experience for students and enhanced cognitive engagement, wider collaboration, and more hands-on student involvement.

Both Button et al. (2018) and Pronnik and Moni (2006) describe case studies which embed open and reproducible scholarship through working in partnership, or engaging in co-creation, with students. This appears to be a particularly useful mechanism to improve engagement. Such an approach is described explicitly by Ryan (2020), who developed 'a *students as researchers of their curriculum'* (SAROC) approach. Ryan (2020) then used the SAROC adoption to investigate the reflective thinking and understanding of students in a teacher education programme, calling into question what students perceived *being a researcher* to mean, along with other learning outcomes. The impact of this case study was qualitatively investigated; through a thematic analysis, a small group of students ($N = 8$) were recruited to evaluate the SAROC programme. This evaluation demonstrated that students' use of self-reflection and understanding of the research process was improved via the SAROC approach. When students worked as researchers and co-creators of their curriculum, this helped them to reflect critically upon the whole research process, be more engaged in the research, and generally start a process of "*becoming researchers*" (p. 644). Ryan (2020) also suggested that the SAROC can lead to the development of ownership and independent thinking in education, which are explicitly related to the cognitive aspects of student

engagement.

Engagement in Open Research Behaviors

Implementation of open and reproducible scholarship tools may also positively influence the down-stream behavioral aspects of student engagement, such as enrolment in the course, engagement with the learning materials, and future uptake of open research behaviors. For instance, a case study reported by Çetinkaya-Rundel and Ellison (2021) observed that introducing open educational resources, specifically reproducible computing skills, within a data science course led to increased enrollment in the class in subsequent years, indicating that including open scholarship practices might indeed increase students' participation in learning discipline-specific skills. Beyond the explicit embedding of open and reproducible scholarship tools and practices into the curriculum, implementing open resources into undergraduate teaching and learning can increase engagement with the subject content, due to the accessibility of the class materials. For example, Sanchez et al. (2021) adopted open educational resources and evaluated this with students. Students in the evaluation noted that the use of open resources was also more accessible and easier to engage with, which improved students' overall engagement with the materials. For example, one student in the evaluation explained that "*Most books I read for classes are impossible to understand, but I am excited because I know the professors speak down to Earth.*" Therefore, this suggests that integrating open materials, as well as an explicit concern for open research *itself,* can also be a useful way of improving student engagement in a teaching and learning context (see also Lindshield & Adhikari, 2013). On top of accessibility, combining open educational resources with further open pedagogy in teaching has also been found to increase student engagement through increased perception of agency. Tillinghast et al. (2020) investigated perceived differences between using only open resources versus combining open resources with an open pedagogy in teaching, including open scholarship specifically.

Overall, they found that there was not much of a numerical difference in engagement between the two, as both were perceived as being of good quality and easy to use. However, expressions of increased student engagement were noted across qualitative interviews, where one student stated "*it was really cool that we got to contribute in some way, and it was interesting for us as students. Not just something that the teacher assigned. We sort of had some control over it*" (p.10).

There was a plethora of research in our review that discussed the consequences of utilizing open educational resources specifically. For example, Bloom (2019) randomly assigned students in an introductory English course to one of two forms of assignments; students either edited openly accessible resources or completed traditional assignments, i.e. creating materials that have no value other than being graded. Students editing open educational resources on average produced somewhat fewer (4.9 versus 5.8) examples in an essay, although a formal result of a statistical test was not provided. Potential reasons were not explored; however, due to divergences in the course content because of the different forms of assignments there were also differences in the requirements for the essay, which also might have impacted the results. Elsewhere, Nurse and Staiger (2019) reported on students learning the topic of reproducibility through service learning; defined as working with community members to develop an intervention on shared understanding. Within their paper they outline how within their social statistics class students partnered with a local non-profit agency collecting and analyzing data compared to a control group who received the information via a more traditional lecture format. Although students who completed the service-learning task reported greater knowledge of what reproducibility is as a concept, compared to those who learnt via a traditional lecture format, assessing student attitudes, confidence, or behaviors towards reproducibility upon completion, there was no significant difference, although inferential statistics and effect sizes were not presented within the paper

so such findings must be taken with caution.

Finally, beyond the undergraduate experience, there was also evidence here to suggest that open scholarship may impact postgraduate students, such as doctoral students. For example, Hare et al. (2020) also reported increased engagement in 34 doctoral students in education learning about open access, both for scholarly work and educational content (in a course designed itself within the principles of open education). In a qualitative analysis of forum discussions and answers to the course evaluation, the authors found developing mastery to be the dominant theme, which they describe as reflecting students' engagement with the content in a process of sense making. Although a small portion of the text data conversely suggested that students demonstrated *resistance* to take steps towards open scholarship, the authors' interpretation suggest that this might be underlined more by a lack of self-confidence, as opposed to a lack of engagement.

Overall, our review demonstrates that open scholarship can provide many benefits for student engagement, whereby the open educational resources and the collegial work environment facilitate their personal growth as *science communicators* and *research collaborators* (Zapata, 2020), while the open scholarship practices empower them (with skills and competencies) and inspire them (with motivation) to engage as *science contributors* to the collective wealth of knowledge (Becker, 2020). Hence, the popularity of studying the impact of open scholarship practices and especially using open educational resources in undergraduate teaching has increased in recent years; yet, research in this area is sparse, lacking systematic approach as to how open scholarship affects: a) the different aspects of student engagement including the behavioral, affective, and especially the cognitive aspects of student engagement (e.g., focus, attention, concentration); b) ways the students can engage academically in learning, teaching and research; as well as c) the student surroundings for active engagement including peers, faculty and community (Groccia, 2018). Furthermore,

research on teaching open scholarship does not yet reflect the broad spectrum of open scholarship practices and, to date, has mainly focuses on teaching reproducible computing, e.g., through using open source software and version control. In this section, we have summarized the existing evidence on the link between the open scholarship and student engagement in research and mapped the areas of further investigation.

Impact of Open and Reproducible Scholarship on Students' Attitudes Towards Science

Finally, the third thematic category identified by the literature review and driven by our research question was the impact of open and reproducible scholarship on students' self-reported *attitudes towards science.* We broadly defined attitudes as individuals' positive, negative or neutral feelings about certain behaviors, topics or practices (Ajzen & Fishbein, 2005). As open scholarship norms and practices have emerged and changed dramatically over the last decade (Azevedo et al., 2022), the attitudes of academics and researchers towards initiatives and reform surrounding transparency and rigor have been diversifying, evidencing hope for transformative change, and concern surrounding the practicalities of implementation (e.g., Hardwicke et al., 2022; Serghiou et al., 2021). In this section, we present and synthesize the empirical findings on students' attitudes towards practices of open and reproducible scholarship, reflected by students' self-reported feelings towards, and perceptions of, engaging with such practices.

Students' Attitudes towards Science

Our review demonstrated that, although students' attitudes towards science can be shifted through one stand-alone class, these changes are not necessarily large, temporally stable, or translate to behavior. For example, Chopik et al. (2018) reported a significant modest decrease in psychology students' trust of the scientific work done by psychologists following a one-hour lecture on the replication crisis. Furthermore, this work evidenced no impact on the students' intentions to pursue graduate study, suggesting that student

recruitment and career pathways are unlikely to change. Similarly, Sacco and Brown (2019) investigated the effect of a one-hour training module on QRPs, targeted at psychology graduate students. The module covered the implications that QRPs can have across science, the public, and researchers' reputation. One week after this module, students reported trusting the findings of psychological studies significantly less. Importantly, Sacco and Brown (2019) reported that the effects of training graduate students to identify and evaluate QRPs are transient, with benefits diminishing in the two months after the training session. Therefore, more sustained efforts embedded within programmes may be required in order to maintain students' awareness/concern in the longer term.

Furthermore, there is evidence to suggest that embedding open scholarship tools into teaching and learning contexts does not always translate to subsequent behavior, in the context of attitudes towards science. For example, Marwick et al. (2020) integrated replication across an empirical archaeology course. After a class assignment that centered around replication, students self-reported that while there is perceived "value of replication for archaeology in general, they do not see any specific benefits to doing it themselves" (p.82). Whilst students often understand the wider implications and importance of replication work, the implications for themselves, and their own research skills and careers, are infrequently discussed.

There was also further evidence in our review of the effects of embedding open and reproducible science across full modules, syllabi and assessments. For example, Hanna et al. (2021) designed an undergraduate module that introduced students to open research and reported that students expressed a general positive attitude towards open practices after taking the module. Hanna et al. (2021) also identified that key benefits, in terms of student attitudes, were for transparency, collaboration, and research progress. For example, one student reported in the module feedback that they viewed open scholarship as "mutually beneficial

for all scientists and society" and another reported that open scholarship offers a "good foundation for future science projects". Truan and Dressel (2021) also investigated attitudes towards and experiences of students with practices of open education, through a seminar about research-based linguistics. Students produced written narratives and then completed a quantitative survey on (1) their willingness to upload and publish academic-based posters in Open Access, (2) teaching concepts in the form of open educational resources, (3) their own reflections on their personal experience of engaging with Open Access. Qualitative analysis focused on students' motives to publish their work using open practices. Results evidenced positive attitudes towards open scholarship practices and students' key motives to use such practices related to a sense of belongingness, personal educational rewards, and active engagement in a collaborative spirit. However, students also reported attitudes related to their fear of visibility and copyrights of their work, as well as concerns about licensing.

Finally, Nurse and Staiger (2019) integrated open code practices in an introductory statistics course as part of an undergraduate sociology program. The authors report a case study, in which they paid particular attention to conveying to students both a) practical knowledge and b) best practices around reproducibility, such as the importance of annotating code. At the end of the course, the lecturers surveyed students' attitudes, future plans, knowledge, and confidence regarding reproducibility in comparison with a class that did not practice reproducibility. The students had better knowledge about what reproducibility is and how it can be achieved, but they reported no added value relating to attitude, confidence, and future plans when compared to lectures alone.

Assessment of Scientific Quality

Beyond reported trust in, or attitudes towards, science, open and reproducible scholarship in pedagogy may also impact how well students are equipped to make assessments of scientific quality and credibility. Again, our review demonstrated that the

implementation of open and reproducible scholarship can have benefits to postgraduate, as well as undergraduate, research training. For example, prompted by the current crisis of low confidence towards psychological science, Sarafoglou et al. (2019) introduced a Masters-level course for research students, which discussed good research practices and was structured using the book '*The Seven Deadly Sins of Psychology'* (Chambers, 2019). The course included topics related to procedures of replication of studies, steps for pre-registering current research and open public sharing of data and analytic procedures, and students were given the opportunity to engage in active discussions about open scholarship practices. Student feedback demonstrated that students' attitudes and feedback were positive and that students showed interest in discussions on these themes, as well as appreciation of the importance of teaching practical skills of open scholarship engagement. On the other hand, students also reported that they felt pessimistic after learning about the replication crisis and crisis of confidence towards psychological science. This indicates that information about low replicability may reflect a more accurate perception of their field, however, may have unintended consequences for (psychology) students' attitudes towards science. Finally, students reported an increased sense of responsibility in dealing with research projects, where they have the opportunity to apply open scholarship practices. There is clearly a need for targeted efforts to improve graduate students' assessment of scientific quality. For example, Pan (2021) explored graduate students (mis)perceptions about responsible conduct of research. Graduate students in this study were given a test which measures students' justification of ethics and research responsibility. Findings suggested that graduate students were generally able to judge the ethical acceptability of scenarios in the test but could not always explain their judgements; while conclusive inferences cannot be drawn from one sample, this may indicate a gap in current training provision in some contexts.

One important aspect of students' research training is through their undergraduate thesis, which represents a promising opportunity for students to change their understanding and attitudes to science. Krishna and Peter (2018) investigated the attitudes of German students towards QRPs and use of such practices in their Bachelors and Masters theses research. Overall, perceptions of supervisors' attitudes towards QRPs predicted variance in both attitudes towards science and use of QRPs. Interestingly, while supervisors' perceived attitude was a significant predictor, neither supervisors' perceived expectation of the positive results nor the students' belief that positive results constitute superior science were related to the students' engagement in QRPs. On a more optimistic note, the authors concluded that while the self-reported prevalence of QRPs among student researchers is somewhat comparable to those more senior, their endorsement of these practices is lower. As they sum up: "*early-career psychological scientists do not like QRPs, but may still feel pressured to use them*" (Krishna & Peter, 2018, p. 17). Considering the attitudes of early career researchers towards QRPs, and the direct relationship between their endorsement and engagement in QRPs with perceived supervisors' attitudes, it is reasonable to assume that direct mentoring could play a pivotal role in shaping current and future research practices of undergraduate and graduate students. This work clearly highlights how Higher Education structures and power dynamics, such as those between staff and students, can either facilitate or restrict the uptake of open research behaviors. A similar conclusion is reached by Olsen et al. (2019), who argued for the promotion of open scholarship in economic postgraduate student supervision, in order to foster critical reflection on scientific literature. However, despite these recommendations (see also Pownall, 2020) our review also showed that there is little empirical work that directly investigates how incorporation of such an approach can impact student outcomes.

To summarize, our review tentatively suggests that efforts to increase awareness and understanding of open scholarship are capable of modestly influencing students' attitudes towards science. Furthermore, applied tasks appear to have additional value for supporting practical experience and skill development beyond lectures or information-giving interventions. However, much of the work presented here relates to modest pre-post intervention comparisons with insufficiently validated attitudinal measures, limited use of control groups and longitudinal designs to determine sustained effects, and evaluates practices which are highly contextualized in local environments. Given such deficits across the literature, collaborative attempts to conduct robust evaluations should be prioritized to provide robust and convincing evidence for impacts of open scholarship upon student attitudes towards science.

Discussion

This review of the literature aimed to synthesize the existing evidence on how embedding open and reproducible scholarship in teaching and learning may impact student outcomes, including students' scientific literacies, student engagement, and attitudes towards science. Our review has demonstrated the current literature in this area, and generally suggested that embedding an open and reproducible scholarship approach into teaching can confer benefits to students in the short, medium, and long-term. We found evidence to suggest that adopting an open and reproducible scholarship approach can positively impact the student experience, most notably in areas such as strengthening students' scientific literacies and offering creative ways for students to engage with their research training. However, we also highlighted that the strength of evidence can be improved throughout, and there are examples in our review where adopting an open and reproducible approach did not impact students' behaviours. This review ultimately aimed to contribute to the appreciation of how open scholarship may have impacts in teaching and learning contexts, which is a

necessary pursuit to continue advancing the robustness, reproducibility, openness, and transparency of research and scholarship. To provide context and wider implications to each section of this review, we now provide summaries of the core findings across the three themes of this review, before discussing limitations of this evidence and implications for practice.

With the cultural landscape of an increased emphasis on *scientific literacies* as a core output from Higher Education, our review generally concluded embedding open and reproducible scholarship into teaching can impact students' ability to *consume* and *conduct* scientific research. Consumption of scientific research involves reading, critically appraising, and evaluating research findings. Conducting research includes competencies in actions, such as research design (e.g., experiment preparation or data collection) and data analysis (e.g., statistics). Using this as a broad framework, our review found three broad areas under the scientific literacies umbrella category that can be impacted by the implementation of open and reproducible scholarship: (1) *the understanding of open research, (2) the consumption of science,* and *(3) the development of transferable skills.*

Several case studies and reports on the implementation of open scholarship pedagogy (e.g., CORE, CREP) demonstrated that introducing open and reproducible methods can increase understanding and consequences of responsible research practices, as well as support undergraduates to *conduct* open research. Thus, there is evidence that embedding open and reproducible scholarship can help students' consumption of science, through increased understanding of the research process, peer review, and statistical analyses used in the published research. Open and reproducible scholarship can also aid the development of transferable skills by giving students opportunities to work with real 'messy' data, draw their own conclusions from real data, and thus begin to understand the strengths and limits of different statistical methods. Additionally, open scholarship can create new opportunities for

students to develop other skills, including teamwork, communication skills, scientific writing, and to foster a greater sense of agency over their research. Such skills are useful for students in many careers, but invaluable for those entering academia (Giuliano et al., 2019).

Secondly, our review demonstrated the potential value of embedding open and reproducible scholarship into teaching for *student engagement*, including factors such as motivation, confidence, collaboration, and co-creation. In line with these factors, a key theme repeated throughout the literature was the notion that open scholarship can improve student engagement through lowering barriers to participation across Higher Education, particularly with research. Notably, the widespread use of open-source learning materials can make valuable knowledge more accessible to all, and particularly for students who are historically marginalized in Higher Education. Furthermore, student involvement was greatly motivated due to the value that open scholarship teaching practices placed on opportunities for students to share ideas, build professional and personal networks, or upskill their research practices. This benefit was particularly prominent in under-represented communities. Open scholarship also widened the adoption of open research behaviors, which was most effectively achieved in consortium-based projects, where students work collectively with other students and staff across several universities on a project or large dataset using robust and open research practices. Similarly, our review also highlighted how research on the effects of open research practices on student engagement were mostly, although not solely, focused on the introduction of open educational resources. In many cases, use of student-curated open teaching resources increased accessibility of materials, perhaps especially for those of lower socioeconomic status or with visual disabilities for whom access to regular materials was limited due to cost or inflexible formatting. Use of open educational resources can also involve the co-creation of course materials with students and faculty, which has shown increased student engagement in terms of collaborative activities and involvement with

science.

Finally, we reviewed the literature that focuses on students' *attitudes towards science.* The reviewed papers found an imbalance between acknowledging the importance of open practices and implications for students' behavior. We found evidence that although single teaching sessions might change student attitudes short term, much more considerable focus on open research practices is necessary to make sustainable change. While there is initial evidence that teaching open practices can enhance students' attitudes towards science, the students do not always think that open practices are relevant for their own work. Apparently, students have a similar attitude to more established researchers, reporting similar concerns (e.g., with copyright or licensing issues). Furthermore, two key components arising are the trust students have in science and their ability to assess scientific quality. These two aspects are not only important considering the future role of students as potential researchers or decision makers, but also as citizens. Making students aware of the replication crisis is certainly an important task. However, it is important to ensure that students do not complete courses with a decreased trust in scientific work, but instead, develop a positive attitude towards open practices as a means to avoid unreproducible research. Consequently, it is crucial to avoid a change from being critical about scientific findings (an important task in science) to losing trust in science.

Limitations

Our review served to synthesize the existing evidence which explores how embedding open and reproducible scholarship into teaching can impact the student experience. However, our review highlighted that there could be improvements in the methodology, reporting, and transparency of empirical research within the pedagogical literature that examines the impact of open and reproducible scholarship. One limitation of our review is the methodological and analytical robustness of the evidence that we draw our conclusions from. Indeed, to make

comprehensive conclusions from this literature, the values of rigorous, thorough, transparent, and methodologically robust science should be applied to this literature. For instance, some empirical studies identified by our review had no control groups, and this lack of experimental manipulation means that it is difficult to draw causal conclusions as to whether responses from students were a *direct* result of inclusion of open scholarship practices. In addition, there is a lack of reporting standards across this literature. For instance, some of the studies in our review did not report any numerical results, instead focusing on anecdotal feedback, and some sample sizes were unjustified or small. This may be problematic for reproducibility, making findings less verifiable, credible, and informative.

Therefore, we recommend that scholars wishing to formally evaluate their pedagogy should employ more Team Science approaches, that focus on collaboration and data sharing, to offer a practical solution to the methodological limitations observed in the empirical studies. As a wider point, the robustness of the open scholarship evidence itself should be subject to wider scrutiny in future contributions in this area. Put simply, open scholarship research should adhere to the rigorous standards of open scholarship itself. We thus also recommend that future open scholarship research abide by rigorous standards regarding methodology, reporting, and transparency, by, for example: (1) implementing control groups when possible; (2) adhering to rigorous reporting standards and reporting clear and transparent results when possible; and (3) employing larger sample sizes and justifying sample sizes, when possible.

Secondly, in terms of limitations, it is important to note that our literature search showed that very few published studies report null or inconclusive findings; therefore, it should be noted that publication bias may likely influence the validity of the published literature. Publication bias is defined when the evaluation of a study's publishability disproportionately hinges on the outcome of the study with the inclination that novel and

significant results are worth publishing more than replications and null results (Rosenthal, 1979). This is an issue because, especially in the field of psychology, there is an inflated and disproportionate rate of positive significant findings in the traditionally published literature (Poldrack et al., 2017; Simonsohn et al., 2014). Whilst the prevalence of publication bias across the social sciences is well established (Open Science Collaboration, 2015) this may extend to the literature on student engagement, open educational resources, and open scholarship behaviors (e.g., data sharing, pre-registration). The claims of open scholarship and student engagement can be corroborated themselves by implementing open scholarship behaviors, such as preregistration and Registered Reports (see, for example, Pownall et al., 2021a). These behaviors can act as a useful tool to quality check, verify and paint a more realistic picture about student engagement and open educational resources. For open scholarship to facilitate research transparency fully, all aspects relating to the scientific process (e.g., publishing data, materials, and details needed for data analysis) are required to be made openly available (Poldrack et al., 2017). As a result, and where possible, we encourage this field to adopt open scholarship practices to overcome publication bias and aid transparency.

Finally, it is important to note here that some of the literature highlighted by our review may be discipline- or context-specific, and not designed to be widely shared or applied in our contexts. For example, there may well be case studies shared here that cannot be transferred to other teaching and learning contexts, due to course accreditation requirements, staffing levels, and nature of the student cohort. Therefore, we encourage educators to take the findings of this review as a useful starting point, before critically and creatively considering how these findings may be applied within their own local contexts. Furthermore, we also appreciate that there are likely to be valuable and insightful evidence of the impacts of embedding open and reproducible scholarship that is not reflected in the

formal published evidence identifiable by our review. While we made attempts here to locate gray and unpublished literature, there is likely to be evidence that supports (or, indeed, refutes) the claims made in this review that we are unable to access, for example, student evaluations or student surveys without consent to share. Therefore, we also recommend that educators and scholars consider interventions to promote and incentivize the sharing of student evaluations in ways that are ethical, thoughtful, and robust. This may include, for example, wider emphasis on pedagogical research and evaluation in teaching and learning contexts.

Implications

We hope that this review 1) provides educators with an evidence-based rationale for embedding open and reproducible scholarship within teaching practices, and 2) demonstrates multiple ways that this goal can be realized across manifold teaching and learning contexts. Higher Education is fundamentally about creating and evaluating knowledge; educators create curriculums and courses, students develop understanding of this knowledge, and Higher Education communities are created. Team Science is an approach that can be used to develop this community, by allowing the student and staff network to interact more through co-production, or with peers and researchers at other institutions; to expose students to better practices; to feel less isolated; and to be valued as part of a team. As a result of this interaction, students are able to think deeper and be more up to date with research practices. Put simply, a positive attitude can be encouraged towards participating in Team Science and knowledge exchange. It is this development and transformation of knowledge that higher education crucially offers to society. Embedding of such an approach is possible with the use of open educational resources, which encourage accessibility of the class materials, allowing them to be easier to engage with. Open educational resources would allow us to transform how knowledge is integrated in teaching and learning and how it can be disseminated from

professors to students, teachers and society. Finally, this would encourage the students to feel that they can contribute to their own learning and that they have agency and choice to learn as much as possible. Therefore, open educational resources can improve attitudes towards science and positive feelings about the project having a use beyond their module.

The findings of our review fit well with the Universal Design for Learning (UDL), a framework to improve and optimize teaching and learning for all people, based on scientific insights into how humans learn in Higher Education (Burgstahler & Cory, 2010). The evidence highlighted that choice should be provided to enable students to develop agency in their own learning. However, there are structural barriers that are encountered in this endeavor, particularly in the context of creating new open educational resources. Thus, open educational resources would be required to make learning more accessible and meaningful as opposed to being more work than help. For instance, elsewhere in the literature, lecturers have discussed the benefits of lecture capture (Nordmann et al., 2021), because it allows students to learn in an environment that suits them, to learn at their own pace and to develop their own speed (Nightingale et al., 2019). Open educational resources allow students to have an opportunity to develop agency in their learning, thus be more engaged with the materials and be motivated in a similar way that scientists are being motivated to work on a specific problem. Open educational resources would allow the academic researcher and student to engage in a way that fits the teacher's style and the learner's preference that can improve creativity and new perspectives which would otherwise be ignored or not considered. Last but not least, open educational resources promote and facilitate social justice and equality. Thus, we reassert the importance of open scholarship, specifically open educational resources, as being a tool to improve our knowledge when thinking about student engagement, a form of universal design for learning and the development of teaching and learning in Higher Education more generally.

It is worth noting here that we have focused our review on undergraduate and postgraduate students within Higher Education, on the basis that there is little-to-no evidence considering the potential implications for introducing open scholarship at other education levels. Outcomes are unlikely to be unique to Higher Education students; therefore, there may be some value of such pedagogical work earlier in the education pipeline, or indeed across the general population through citizen-science, given the possibility for such work to support domain-general skills around scientific literacy. This work may help address the growing societal needs to tackle dis- and misinformation, conspiracy theories and evidence manipulation. In addition, this work enables the student, regardless of what career path they may choose, to be a more critical consumer of research, consequently allowing them to develop confidence in challenging outdated dogmas, stereotypes and prejudiced viewpoints. Furthermore, it is also important to appreciate that engagement with open scholarship practices may have unintended negative consequences that our review has not captured. For example, some scholars have raised concerns surrounding the workload that open science adds, and the need for open science discourses to be more compassionate and welcoming (e.g., see Whitaker & Guest, 2020). Therefore, we encourage educators to also investigate the potential negative and/or unintended consequences of engagement with open research for students and early-career researchers (see Kowalczyk et al., 2022 for a useful guide).

Conclusion

Our literature review has indicated that explicitly embedding open and reproducible scholarship into Higher Education can clearly enhance student engagement, scientific literacy, and attitudes. Furthermore, our review also demonstrated that there remains an imbalance between students' attitudes and students' behaviors, whereby students often do not see the relevance of open scholarship to their own work, posing a useful area for future follow-up studies and interventions. While there is promising ongoing work in this area,

including discussions surrounding the pedagogical value of open scholarship (Chopik et al., 2018) and current Registered Reports that directly and empirically assess the impact of open scholarship on student attitudes (Jarke et al., 2022; Pownall et al., 2021b), further empirical research should continue to investigate how embedding open and reproducible science in teaching can affect student outcomes. Beyond our review, there are examples of best practice embedding of open and reproducible scholarship which were not included here, due to the lack of concrete information regarding student outcomes (e.g., Kathawalla et al., 2021; McAleer, 2021). Such examples provide a useful framework for integrating open and reproducible science in different levels of the student experience in a range of contexts. These are shared in supplementary information accompanying this manuscript: https://osf.io/4jqbw/. Finally, it is important to stress that the values of open, robust, transparent, and rigorous research should be applied to pedagogical research and teaching evaluations, in order to have the best evidence possible to determine the impact of open and reproducible scholarship. In sum: robust research requires robust teaching, and vice versa.

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Note: References marked with * were obtained by the systematic review

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