Research in Science & Technological Education

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/crst20

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To cite this article: Bénédicte A. M. Brahic, Shijie Miao, Simon J. Webb & Alison G. Harvey (04 Jan 2024): Reflexive, relevant and interactive: a STEM student-centred pedagogical approach for responsible research and innovation (RRI) training in higher education, Research in Science & Technological Education, DOI: 10.1080/02635143.2023.2296430

To link to this article: https://doi.org/10.1080/02635143.2023.2296430

RESEARCH IN SCIENCE & TECHNOLOGICAL EDUCATION
https://doi.org/10.1080/02635143.2023.2296430

Routledge
Taylor & Francis Group

Reflexive, relevant and interactive: a STEM student-centred pedagogical approach for responsible research and innovation (RRI) training in higher education

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ABSTRACT

Background: Whilst Responsible Research and Innovation (RRI) principles are increasingly informing and shaping Science, Technology, Engineering and Maths (STEM) research narratives and practices, the training of higher education (HE) STEM students in RRI is still developing, creating a mismatch between training provision and sector practices and expectations.

Purpose: Training of HE STEM students in RRI principles is a key component of the long-term changes RRI frameworks hope to achieve. However, little is known about postgraduate (PG) students' awareness of, perceptions of and attitudes towards RRI, despite the pedagogical implications. This paper offers grounded insights and recommendations to shape this emerging area of pedagogical research and practice.

Sample: Forty-nine PG STEM students with a range of nationalities enrolled in six UK higher education institutions. Most students had not received prior formal RRI training, although a small number of students who had received some RRI training were selected for comparative purposes.

Design and methods: An exploratory, small-scale student-led, mixed-methods study that investigated PG STEM students' engagements with RRI. Key objectives were to assess awareness and knowledge base; explore attitudes towards RRI; gauge the impact of the COVID-19 pandemic on RRI engagement; identify student preferences in relation to RRI training.

Results: The data points to the importance of individual characteristics and cultural backgrounds in shaping students' engagement with RRI, as well as the significance of the context of student engagement with RRI. Although generally unaware of formal RRI frameworks, respondents provided examples of RRI that were drawn from national/cultural contexts. The perceived relevance of RRI varied with training level (Masters' or PhD). A preference for interactive training in RRI was expressed, with some students commenting on the challenge of becoming reflexive practitioners.

KEYWORDS

Student-centred pedagogy; Responsible Research and Innovation; Higher education; postgraduate science courses

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Supplemental data for this article can be accessed at https://doi.org/10.1080/02635143.2023.2296430

Conclusions: This study provides important evidence to inform the pedagogical approach to RRI in HE STEM training, which the authors argue ought to be supported, reflexive, relevant, and interactive.

Introduction

Principles of responsibility are increasingly central to research and innovation (R&I) in the Science, Technology, Engineering and Mathematics (STEM) disciplines. Governance frameworks, such as those based on 'Responsible Research and Innovation' (RRI), seek to embed reflection on the societal and environmental impact of R&I in STEM as part of their development processes. Whilst RRI, which some have described as a paradigm shift (Arnaldi, Gorgoni, and Pariotti 2016; Lindner et al. 2016), is increasingly informing and shaping STEM research narratives and practices, it is still developing in the training of STEM scientists in higher education (HE). In this paper, we discuss common challenges that have been identified when implementing RRI in HE and suggest that this leads to an apparent mismatch between training provision and sector expectations, which produces a range of consequences. At an individual level, it means students are ill-equipped to engage with this aspect of scientific enquiry and practice, as well as the professional opportunities associated with it. At societal level, this mismatch is a missed opportunity to foster better dialogue between the scientific community and wider society.

Given the ongoing development of several assessed RRI courses for PhD students in the UK (Stahl et al. 2023), understanding students' pre-existing perceptions and attitudes towards RRI has important pedagogical implications for HE institutions: where to start?; what and how to teach an increasingly diverse population of students?; how might prior knowledge improve student learning outcomes? However, little is known about STEM students' engagement with RRI (knowledge base, attitudes, and perceptions) prior to engaging in formal RRI training. This gap in knowledge poses several research questions that this paper seeks to address: how might students from large and diverse cohorts engage with RRI? How do they perceive its relevance and value, particularly with respect to their education as scientists and their future career aspirations?

Based on an exploratory, student-led, mixed-methods study of STEM students' perceptions and attitudes towards RRI, this paper explores students' engagement with RRI and uses this information to suggest an evidenced-based pedagogical approach to develop HE RRI provision. First, relevant contributions to the field are discussed to explore the mismatch between the development of RRI as a central operating framework in STEM R&I, and its relatively recent and emergent embedding in HE STEM education. Then, the methods and study sample underpinning this paper are outlined before findings are discussed. Finally, evidence-based recommendations for student-centred pedagogy in the learning and teaching of RRI in Higher Education contexts and the training of future STEM scientists are formulated.

Background

The emergence of RRI in STEM

Increased societal awareness of the impact of R&I on wider society has led to the emergence of a governance 'vision' for formalising the responsibilities of researchers. This concept has become known as Responsible Research and Innovation (RRI), where decisions about the directions of R&I are consciously made by researchers with societal impact in mind. RRI aims to bring actors involved in all stages of R&I under one umbrella at the interface between science and society (Owen, Macnaghten, and Stilgoe 2012), making R&I more open to input from other voices, e.g. social scientists and public voices.

The concept of RRI has been promoted by the European Commission (EC) since 2010 and was defined by Rene von Schomberg (2012) as:

> . . . a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products (in order to allow a proper embedding of scientific and technological advances in our society).

Since then, the European Commission, EU Member States and associated countries have launched various initiatives and activities under the name of RRI, aiming to take the concept from social sciences into R&I policy, then implement these concepts in STEM academia and industry.

RRI was a core component of Horizon 2020 and focussed on eight key aspects: Gender Equality, Open Access, Ethics, Governance, Science Education, Stakeholder Engagement, Social Justice and Sustainability (Roger et al. 2015). The overarching ethos of RRI, as defined by Horizon 2020, centres around concepts of diversity and inclusivity, openness and transparency, anticipation and reflectiveness, and responsiveness and adaptivity. National and discipline-specific frameworks for RRI have also been developed across Europe, including the UK-based Engineering and Physical Sciences Research Council (EPSRC, the largest funder of engineering and physical science and innovation in the UK), 'AREA' framework. This framework comprises four parts: Anticipation, Reflection, Engagement and Action (Stilgoe, Owen, and Macnaghten 2013).

Much of the original discourse around the development of RRI drew from the governance of genetics and life science research (Zwart, Landeweerd, and van Rooij 2014) and focussed on ongoing governance challenges in new research fields. These include nanotechnologies (Karinen and David 2009; Nano2all 2016; Pidgeon et al. 2004), geoengineering, information and computer technologies (ICT) (Jirotka et al. 2019), and synthetic biology (Ribeiro and Shapira 2019; Shapira and Kwon 2018; Shapira, Kwon, and Youtie 2017; A Synthetic Biology Roadmap for the UK 2012).

Emerging fields already subject to an RRI focus tend to be related to global challenges, such as climate change, sustainability and healthcare. This correlates with the embedding of global challenges, social responsibility and the UN Sustainable Development Goals (SDGs) in higher education curricula (Kioupi and Voulvoulis 2020; Lopez 2022; Nhamo and Mjimba 2020). Simultaneously with (and independently of) the development of RRI, the past decade has seen an increase in inclusivity initiatives (Claeys-Kulik, Ekman Jorgensen, and Stober 2019). These principles of Equality, Diversity, Inclusion and Accessibility (EDIA) are included in various RRI initiatives (Smith, Manzini, and Ives 2022)]. For example,

Nano2all´s activities verified that there is a deeply felt need for inclusiveness and integration of societal perspectives in the nanotechnology R&I ecosystem (Nano2all 2019).

The unpredictability of long-term consequences of R&I is a common theme across these emerging fields. This reflects the Collingridge Dilemma; by the time we are aware of negative consequences it is often too late to implement change, but early in the R&I process – when changes can be easily made – we are unaware of the full range of potential consequences (Collingridge 1980). This is a common theme in RRI and justifies moving dialogue and RRI governance approaches further 'upstream', linking to education and the training of researchers/innovators from a range of scientific areas.

To enact RRI will involve all actors, all areas of R&I, and all organisational levels. It requires collaborative engagement between physical and social sciences to address global challenges; shared goals between science and society; and upstream consciousness of potential positive and negative consequences.

Evolution, challenges and critiques of RRI

Translation of RRI from a social science and policy concept to its practical implementation has raised several challenges (Levikov, Quacinella, and Duca 2020; Schuijff and Dijkstra 2020; Tassone et al. 2018). With over a decade since the first RRI frameworks, discussion is still ongoing about RRI definitions and implementation. The term itself has been described as being somewhat vague and fluid, with several sources identifying the need for actors to develop their own concepts of RRI for their specific context (Burget, Bardone, and Pedaste 2017; Heltzel et al. 2022; Roger et al. 2015; Stahl et al. 2017; Sutcliffe 2011).

With RRI being applied across all actors and all sectors, its meaning and implementation also depend on the level of the actors in the R&I process. Shelley-Egan, Bowman and Robinson (2018) discuss the need to consider implementation of RRI in terms of micro-meso-macro levels, where macro-level involves national policy decisions, meso-level involves organisations such as funding bodies, and micro-level relates to local decisions, e.g. individual research labs. While there are benefits to the autonomy of context-specific definitions, this can in itself be a barrier to successful RRI implementation (Kuzma and Roberts 2018). With a diverse range of viewpoints on what RRI entails, there is a potential disconnect between stakeholders. Additionally, implementing scientific governance frameworks globally requires recognition that frameworks, such as RRI, are built on underlying social norms and philosophies (Hufty 2011; Meijer et al. 2016), as well as institutional practices (Christensen et al. 2020).

Hartley, Pearce and Taylor (2017) also found a lack of creativity and imagination amongst academic staff in terms of what implementation of RRI *could* look like. They note that while the plurality of RRI interpretations includes radical and progressive approaches, most actually adhere to existing science–society relationships, indicating that aligning RRI with current practices risks maintaining the status quo.

What emerges is that the true embedding of RRI involves voluntary cultural and philosophical changes to R&I practices (Arnaldi, Gorgoni, and Pariotti 2016; Zwart, Landeweerd, and van Rooij 2014). This involves actors taking ownership of the process and defining RRI for their specific context. Both the expert group commissioned by the European Commission in 2015 (Roger et al. 2015) and the long-term Res-aGorA project (Lang and Griessler 2015; Lindner et al. 2016), as well as independent studies (Kwee,

Yaghmaei, and Flipse 2021; Meijer et al. 2016), have highlighted the challenges in retaining this autonomy whilst creating indicators that communicate success at implementing RRI.

A challenge that arises when embedding RRI in academic research practices is the conflict between RRI philosophy and current benchmarking practices in the neoliberal university setting. Moving RRI 'upstream' in an academic setting requires researchers to be aware of and considering RRI. Many career pathways in academia have a focus on outputs and publication record, yet full commitment to RRI philosophies requires value to be placed on RRI activities in the academic setting (Åm 2019; Moher et al. 2020). This is also an issue in EDIA, although changes are slowly making their way into the sector, *via* initiatives such as the Advance HE Athena Swan Charter in the UK (https://www.advance-he.ac.uk/equality-charters/athena-swan-charter last accessed 17.05.2023).

Implementation of RRI in higher education (HE)

With academia and industry as the two main pathways through which graduates become actors in R&I, Owen and Goldberg (2010 pg 1700) have described how publicly funded HE institutes are an important conduit for embedding RRI principles throughout the next generation of scientists:

> … the public funding of research in academic institutions, such as universities, remains a very significant catalyst for disruptive innovation and presents perhaps the earliest opportunity to embed a more reflexive, responsible innovation approach in an operational, real world context.

Full embedding of RRI in higher education (HE) institutions requires training and uptake of the principles of RRI at all levels including institutional policy, academic research practice, and teaching at both undergraduate (UG) and postgraduate (PG) levels (Tassone et al. 2018). Drawing on results from the large-scale Enhancing Responsible Research and Innovation through Curricula in Higher Education (EnRRIch) project, Tassone (Tassone et al. 2018 pg 343) recognised the challenges in teaching RRI in HE effectively:

> Fostering RRI in higher education curricula is about equipping learners to care for the future by means of responsive stewardship of research and innovation practices that address the grand challenges of our time in a collaborative, ethical and sustainable way.

Teaching RRI has been proposed by Mejlgaard et al. (2019) to revolve around *RRI as phronesis* (practical wisdom) rather than '*knowing RRI policies*', emphasising the importance of critical reflection and engagement with external actors. They also highlight some challenges of implementing RRI in HE: institutional reluctance due to resource demands and priorities of disciplinary specific teaching, conflicting demands for societal input in research vs. commercialisation of research, assessments of research excellence that do not align with RRI values, and the risk of RRI as a box-ticking activity. The challenges that are raised repeatedly in these studies reflect competing definitions of RRI (and how to teach this evolving topic), the need for RRI to be centred in the context of the actors involved (e.g. discipline and role), the need for creative thinking and a change in cultural norms, as well as challenges arising from competing priorities (academic milestones, commercialisation, etc.).

Aiming to bring RRI into HE, the Higher Education Institutions and Responsible Research and Innovation (HEIRRI) project, which ran from 2015 to 2018, developed 10 RRI training programmes which ranged from summer schools to massive open online courses. The evaluation of these programmes was based on four criteria: learner satisfaction with the programme, changes in attitudes and knowledge, behavioural change, and organisational changes (Tokalić et al. 2021). However, the evaluation did not question participants' perspectives on the relevance of RRI to their development as scientists or their future careers. Several smaller scale case studies have described different approaches to teaching RRI to students at UG, PG (Masters) and PhD level across STEM disciplines, including creative approaches such as 'speed-date-a-scientist' (Limson 2021), 'Living Labs' (Konstantinidis, Petsani, and Bamidis 2021), 'double-loop' learning approaches (Hesjedal et al. 2020), and how to assess student engagement with RRI teaching in EPSRC-funded Centres for Doctoral Training (CDT) in the UK (Stahl et al. 2023). Common themes that are noted across these various approaches are a focus on reflective practice skills, discussion and collaboration, and inclusive teaching approaches. A special issue in Budapest Management Review (Matolay, Toarniczky, and Gáspár 2021) covered six case studies of RRI teaching in business management HE that highlighted similar themes (Fazeka and Beck-Biro 2021; Juhász et al. 2021; Kiss, Veress, and Köves 2021; Kozma 2021; Neulinger 2021; Zsóka and Ásványi 2021).

While there have been examples of teaching specifically under the heading of RRI, such as the HEIRRI project, much of the education STEM students receive around RRI may come under other headings not directly badged as RRI. For example, research integrity training is an essential component of most science degree programmes, with ethics taught as a standard topic in biological sciences, fields involving personal information sharing (e.g. ICT) (Casañ, Alier, and Llorens 2020), and artificial intelligence (Holmes et al. 2022). STEM outreach programmes that encourage UG and PG students to engage with the public are commonplace in UK HE institutions; the STEM ambassador programme (https://www.ukri.org/publications/stem-ambassador-programme-review-a-report-for-ukri/ last accessed 05.11.2023) provides opportunities for further consideration of RRI topics.

The 17 UN SDGs share some similarities with RRI, so taught HE units focussing on, or including, these SDGs have become more common over the last decade (Chankseliani and McCowan 2021; Franco et al. 2019; Leal Filho et al. 2019; Marouli 2021; Purcell, Henriksen, and Spengler 2019; Zamora-Polo et al. 2019). Sustainability in particular has been a hot topic in recent years with many subject areas from materials science to civil engineering incorporating this topic in their programmes.

Similarly, there have been increasing numbers of HE institutes embedding social responsibility and EDIA initiatives into degree programme curricula. This includes expanding sources of information used in the curriculum, becoming more inclusive and representative, and considering specific EDIA/social justice aspects when discussing research, such as accounting for participant diversity in clinical trials and social justice in geoengineering projects. Existing teaching on RRI-related topics separately means that some fundamental information and concepts are introduced. However, RRI-specific courses may go beyond legal requirements into grey areas with considerations of what it means to be a 'responsible' researcher or innovator. The structures of RRI frameworks require practitioners to be anticipative, reflective and to engage in dialogue. Without combining these related topics into RRI specific teaching, do we miss out on the teaching of these specific, and valuable skills?

The present study

RRI training is likely to expand further in the UK due to increasing public and governmental scrutiny of R&I. As the number of students receiving RRI training increases, future student cohorts are likely to form a more diverse community with different educational, financial, and cultural backgrounds.

This survey of the RRI literature highlights a requirement for social implications to be considered further 'upstream' in the R&I process. Actors, such as STEM students in HE, need training to conceptualise RRI in the context of their discipline and to effect changes to cultural/philosophical norms. As RRI has evolved, several studies have identified specific challenges in implementing RRI in academic settings. These include the need for individual actors to recognise the meaning of RRI in their context (Burget, Bardone, and Pedaste 2017; Heltzel et al. 2022; Kuzma and Roberts 2018; Roger et al. 2015; Shelley-Egan, Bowman, and Robinson 2018; Sutcliffe 2011), the need for voluntary changes to cultural norms and philosophies on a community level (Arnaldi, Gorgoni, and Pariotti 2016; Hufty 2011; Kwee, Yaghmaei, and Flipse 2021; Lindner et al. 2016; Meijer et al. 2016; Roger et al. 2015; Zwart, Landeweerd, and van Rooij 2014), and conflict between RRI philosophies and benchmarking in current academic career progression routes (Åm 2019; Moher et al. 2020). Overcoming these challenges will require appropriate and effective methods for teaching/training the next generation of STEM researchers.

Whilst developing an RRI course tailored for students enrolled on a biomedical materials PhD programme at a UK Higher Education institute, we became interested in how RRI training was received by students and how it could be delivered to a more diverse community. In this paper, we explore what PG (MSc and early PhD) students currently understand about RRI and how they might engage with the topic. Understanding students' engagements with RRI is critical to the development of evidence-led, impactful RRI pedagogies aimed at increasingly diverse learning communities.

Methods

Exploring the views of and receiving the input from HE STEM students on RRI training is key to make RRI training relevant and impactful. With this in mind, the research strategy (choice of research methods and sampling techniques, plans for data collection and analysis as well as ethical approval and compliance) was devised collaboratively by the research team with a representative of the student body. This representative oversaw data collection (administered the exploratory surveys, conducted the interviews) and participated, *via* a research report, in the development of the present paper. Student involvement in the different stages of a research process is thought to benefit the quality of the collected data through facilitating access to potentially 'hard to reach' participants (peer-to-peer access), lower hierarchical differentials between researchers and the sampled cohort, and support the generation of more 'authentic' narratives.

This paper is based on this small-scale exploratory mixed-methods study that investigated postgraduate trainee scientists'/students' perceptions of RRI during the first 6 months of COVID-19 pandemic in the UK (March 2020 – September 2020); in this unprecedented time, society's view of science evolved rapidly with a renewed interest in and appreciation of the value of science among societal actors (Sala-Bubaré et al.

2022). Four key objectives of the project were as follows: 1. measuring the awareness and knowledge base of PG students in relation to RRI; 2. exploring the range and breath of students' engagements with, perception of and attitudes towards RRI, *particularly in the context of their training*; 3. gauging the impact of the COVID-19 pandemic on engagement with RRI; 4. identifying students' preferences in relation to RRI training.

Using a mixed methods explanatory sequential design (Subedi 2016), the study underpinning this paper used two complementary research methods (exploratory surveys and semi-structured interviews) to draw a picture of PG STEM students' perception and attitudes towards RRI, a topic hitherto relatively understudied. The exploratory survey on which this paper is based had four sections that gave participants the opportunity to answer a series of closed and open-ended questions. Headings for the four sections are as follows: (1) 'Getting to know you', (2) 'Knowledge base and awareness', (3) 'Awareness raising, and engaging with Responsible Research and Innovation (RRI)', (4) 'RRI and COVID-19: a student perspective'. Closed questions enabled the research team to get a sense of the broad picture in relation to the four objectives set for the study whilst open-ended questions helped generate new insights on what has hitherto been an understudied topic. The survey questions are available as Supplemental Material for this manuscript.

The survey was first administered online to 49 PG STEM students (aged 21 to 32, 28 female and 21 male, of 7 different nationalities: 5 British, 3 EU nationals, 1 student self-described as Arabian, and 40 Chinese students) enrolled on MSc and/or PhD courses across six UK universities. The sample was gathered through convenience and snowball non-probabilistic sampling (Merriam and Tisdell 2015).

The data generated *via* these exploratory surveys were then supplemented by five online semi-structured interviews with students purposefully selected from the sample of students who completed the initial survey. The students invited to participate in semi-structured interviews had been identified as representative of a range of perceptions and attitudes towards RRI whilst offering insights potentially shaped by their personal characteristics (e.g. gender, nationality/national belonging) and/or their training/courses. The semi-structured interviews followed the same structure as that of the exploratory surveys and included additional prompts on the four themes of the study to give participants the opportunity to expand further on their initial contributions. The conversational format of semi-structured interviews supports the generation of 'richer' narratives and new insights, critical to the in-depth qualitative understanding of understudied topics.

The research described in this study adhered to ethical standards and guidelines according to institutional Research Governance policy. As part of the survey and the semi-structured interviews, informed consent was collected alongside the use of a Participant Information Sheet. Data analyses were performed using anonymised data. Participants were able to opt out of the study at any time. The data collected in the exploratory surveys were entered in Excel to support the identification of patterns in the responses to closed questions as well as emerging codes and subsequent themes of analysis from the open-ended questions. Similarly, semi-structured interviews were transcribed and analysed manually to identify codes and subsequent themes of analysis. The research team worked collaboratively throughout the different phases of the study and data analysis in particular, to enhance its validity and mitigate individual bias.

This is an exploratory study which seeks to open up research and pedagogical perspectives for what currently remains an understudied question (the engagements, perceptions, and attitudes of HE STEM students with RRI). It intends to generate new insights into RRI within STEM higher education, which will in turn help shape research in RRI pedagogy and support future studies that quantify and measure students' engagements with RRI. Whilst the use of mixed methods (exploratory surveys and semi-structured interviews) supports the validity and reliability of the study (Guba and Lincoln 1994), the limited number of participants and the sampling methods chosen mean that the findings may not be representative and are not statistically inferable/generalisable. Nonetheless, the perspectives and insights derived from the data contribute to informing and shaping wider debates and conversations concerned with RRI in scientific training, particularly in HE.

Findings and analysis

Knowledge base and awareness of RRI

One objective of the study was to measure students' awareness and knowledge base of RRI, while recognising that students may have experienced teaching and learning on RRI topics without them being badged as such. In the opening question of the survey, when asked if they had come across the concept of social responsibility in R&I, 20 of the participants (41%) declared they had whilst 17 participants (35%) stated they had not, and 12 (24%) were unsure. Among those who had previously come across RRI (20 participants), nine declared they encountered RRI (or questions linked to RRI) in the news. Other sources (textbooks, lectures, their academic tutors, and friends) were cited, albeit less frequently. It is interesting to note the prevalent role of the news for disseminating RRI among the studied cohort. Encountering an issue *via* the news contrasts with the other 'means-of-knowing' that respondents cited (formal education or conversational interactions, for example); information encountered through the news is more likely to be top-down, removed, with limited space for interaction and co-created reflection. Interestingly, one of the respondents who had declared that she had not come across RRI stated that, after completing the survey, she recognized having encountered RRI in her everyday life and scientific training, although she explained that she was not familiar with the term RRI itself. Her example (and that of a few other respondents) suggests that participants' knowledge and awareness of RRI-related ideas and debates may be greater than they recognize – even though they may not use academic RRI terminology. As RRI is built on pre-existing concepts around scientific responsibility and how science and society interact (Owen, Macnaghten, and Stilgoe 2012; von; Schomberg 2012), it is perhaps not surprising that students encounter these topics without the 'RRI' label. These prior encounters, as well as their experiences as members of the public, may provide a way of encouraging STEM students to engage with the social science aspects of RRI.

Having completed initial questions to gauge levels of knowledge of RRI, participants were asked to write a short definition of social responsibility and innovation. All but four participants engaged with this question, which gave interesting insights in students' understanding of RRI and some of the misconceptions associated with it.

Most of the definitions provided tended to be broad and non-specific, invoking often ill-defined notions of impact, responsibility, betterment/harm and ethics whilst highlighting the link between scientific research, innovation and wider society. In contrast, some definitions limited RRI to the implementation of widely accepted principles of scientific inquiry, such as safety procedures and/or honesty and integrity when reporting research results. Interestingly, one participant engaged in a critical exploration of RRI, questioning its desirability in relation to fundamental research in natural sciences whilst acknowledging its benefits in relation to the development of innovation. The breadth and range of answers (to be read in conjunction with previous questions) highlight the topicality of RRI debates and the interest they generate. They also indicate a lack of systematic engagement with RRI issues in contemporary scientific training. Therefore, while it is possible students are receiving training on the disparate components of RRI, these results suggest that the overarching ethos of RRI is being missed, leading to a risk of maintaining the status quo rather than thinking creatively about what RRI *could* be (Hartley, Pearce, and Taylor 2017).

The question prompting participants to define RRI was supported by a first follow-up prompt which asked respondents to provide an example of RRI. Out of 49 participants, 16 did not provide an answer and/or indicated they did not know, 23 gave broad/non-specific answers and 10 made references to clearly identifiable RRI case studies. Debates associated with cloning were the most frequently cited. The focus of the students on cloning contrasts with reported perceptions of RRI by academics (regardless of their discipline), with the most commonly cited RRI-related public controversy the *'GM crisis'* of the 1990s, which led to the rejection of genetically modified technologies in some countries (Hartley, Pearce, and Taylor 2017). This contrast highlights the relevance of popular media sources in conceptualising RRI and also highlights that RRI is related to individual experiences, which differ by generation. Therefore, teachers of RRI should aim to be aware of their own experiential biases and allow students to voice their own views on what is relevant, building their own picture of what RRI means.

It is interesting to note that respondents who provided identifiable RRI examples typically cited examples from national/cultural contexts they were presumably familiar with; in other words, respondents referred to examples/issues prominent and/or involving individuals prominent in their country of citizenship. Asked to comment on their choice of RRI examples during semi-structured interviews, one participant rationalised his answer as follows: 'firstly, because he is an Italian researcher, and I am Italian . . . '; another respondent who had mentioned environmental pollution explained they had first-hand experience of the example they discussed in their everyday life in China. Students' tendency to relate RRI concepts to their national/cultural background again shows that when implementing RRI, practitioners are building on pre-existing social norms and philosophies (Hufty 2011; Meijer et al. 2016). With the internationalisation of HE, it is important to respect and consider cultural diversity in the classroom when teaching RRI.

Subsequently, participants were invited to give an RRI example in their own research area. Very few respondents provided a detailed and specific answer to this question. Interestingly, students who provided specific examples associated with their area of study declared they had the opportunity to engage with RRI as part of their training/degree and/or to discuss RRI-related issues with a tutor.

Students' perspectives on RRI in scientific training

Having first gauged students' awareness and knowledge base of RRI, the survey then sought to explore the range and breadth of students' engagements with, perception of and attitudes towards RRI, particularly in the context of their training and beyond. This section of the survey opened with a short, one page, text providing a general definition of RRI (among researchers and practitioners in the sector), as well as some background information and a short discussion of the purported impact of RRI (see the Supplemental Material for this one-page text). The intention was to provide respondents with basic elements of knowledge about RRI, as shared among researchers and practitioners in the STEM sector, so they could better identify RRI-related matters in their training and practices. All confirmed they had read the text and 93% felt they understood RRI better.

The overwhelming view among respondents was that RRI was 'essential', 'very important' or 'important' for science and society. Answers became more nuanced when the importance of RRI was evaluated by respondents in relation to different aspects of their experiences as individuals. Interestingly, RRI was deemed essential by 28 participants in their capacity as trainee scientists whilst only 20 thought of RRI as essential in the context of employability – with 10 rating it either 'not so important', 'not important' or declaring they do not know about its importance in the context of their future career. Whilst discourses related to RRI permeate society, accompanied by increased formalisation and discussion in academe, many students find it difficult to connect RRI with their employability and the world of work. This raises some interesting considerations with regard to teaching. Students should be encouraged not only to consider RRI in their immediate research environment but also to consider how RRI might feature in their future careers, for example, through Stahl's Maturity Model (Stahl et al. 2017).

Female students appear more likely to view RRI as important in different spheres of their experience (as a private citizen, as a student, and in their future career). This may partly be due to the nature of their studies and/or their research projects, which in some cases have clear applications with people and living beings. For example, one of the female interviewees discussed applications of her research project in medicine, highlighting how these informed her research work: 'it is important to pursue the safety and the efficacy of the strategies so it can be applied successfully and responsibly'. Gender has previously been noted to affect perceptions of RRI at an academic researcher level (Bührer and Wroblewski 2019), with female researchers more likely to support gender equality activities, take part in public engagement activities, and openly communicate their research. Furthermore, it has been recognised that the lived experiences of women influence their perception of the importance of RRI (Levikov, Quacinella, and Duca 2020).

Follow-up interviews underlined the transformative potential of RRI training on research practices and reflexivity. A respondent described how, despite initially knowing very little about RRI, he became interested in RRI questions through receiving formal training as part of his doctoral studies and now uses this learning to advance his research work and inform associated dissemination activities (particularly noting its usefulness in relation to public engagements).

The growing significance of RRI is generally regarded as a positive development and encounters limited public challenges, although a historical Northern dominance and the epistemic injustice associated with it ought to be noted (Koch and Koch 2020). Nonetheless,

it is important to note that several respondents expressed concerns about RRI. Some respondents hinted that RRI was an interest only the most privileged regions of the world could entertain; these respondents expressed doubts on how RRI-related concerns could be taken on comprehensively in the societal context they hailed from and were, for some, intending to return to in order to start their career. One was concerned RRI could hinder the progress of science. Another student declared that RRI was not relevant to him as a trainee scientist or to his future career as 'the related application is a technician's job, and RRI is something *they* should consider. As a scientist, you only need to consider technological breakthrough and how to expand human knowledge'. This view was echoed by another respondent who felt RRI 'should be handed over to the corresponding popular science personnel'. Whilst some expressed strong reservations (e.g. slowing of scientific development), others had different concerns. One of the respondents felt RRI was important but not their priority as a student 'I should focus on the science in this part of my education and think about RRI later', whilst another felt she still had 'a lot to learn before she could fully apply these things'. These responses align with some of the challenges associated with changing cultural norms and philosophies. van Hove and Wickson (van Hove and Wickson 2017, pg 225) saw similar themes and suggested:

> The fact that what is perceived as good science is not always the same as responsible research does not have to be problematic . . . However, it does become problematic when RRI is seen to not just expanding what is required for good science, but actually pulls against it and comes into conflict with deeply rooted cultural values.

After these questions about attitudes and concerns, the following question concerned the positioning and belonging of RRI within each student's subject area. Most students (41) declared that RRI belonged to their subject area, whilst 3 disagreed and 5 were not sure. Female students (97%) were more likely to perceive RRI as belonging to their subject area than their male counterparts (65%). Whilst a small number of students saw RRI as belonging to 'liberal arts' and 'philosophy', most noted its interdisciplinarity. Students working on projects with clear implications beyond academia (e.g. medicine, biomaterials) and/or with pathways to impact involving animal and human trials highlighted the relevance of RRI and indicated the centrality of RRI to their scientific/disciplinary practices.

Identifying students' preferences in relation to RRI training

Subsequent parts of the survey explored RRI in the context of students' scientific training in HE. Interestingly, when asked about the existence of an RRI provision in their current university course, a significant proportion of the students sampled (17 out 49) declared they were unsure (whilst 12 stated it was taught and 20 stated that it was not). Students' uncertainty could suggest that RRI-related matters are discussed but the term RRI may not be used and/or the concept of RRI explored formally, as (part of) a taught unit and/or a research project. The necessary fuzziness of the concept of RRI may also make it more difficult for learners to identify it. Students were then asked how RRI was taught on their current course. Out of 21 answers (28 did not answer), nine respondents declared RRI was taught by a tutor in a compulsory (1) or optional (8) module dedicated to RRI. Six stated that they learnt about RRI with a tutor as part of STEM science module. Five respondents encountered RRI as part of a self-directed training and one identified another method but did not specify which one.

Almost 82% of participants (40) wanted RRI to be taught in their current degree, with all PhD students believing that RRI should be taught in their current degree compared to only 79% of Masters level students. One PhD student who had participated in RRI training as part of his course thought RRI should be taught as a compulsory module as it gives trainee scientists an idea of how important their research is and enables them 'to see all the areas that their research can affect'. He then explained that RRI helps develop a more comprehensive and holistic view of the scientific world. In contrast, a Masters student declared that RRI shouldn't be taught as adding another course into their studies would make students 'feel very tired'. The student also explained that people should already understand 'RRI related things' from their daily experiences (citing social responsibility and ethics) and that this knowledge can be acquired from the news or *via* books and does not require a dedicated unit in their degree. Another student shared a similar perspective, declaring that it was not important for him at this moment and that he should focus on scientific research (which he regarded as separate from RRI).

When asked how RRI should be taught, 33 of the respondents indicated that they wanted RRI to be taught by a tutor whilst 15 preferred a self-directed method of learning. Whilst half of PhD students were in favour of RRI being taught as a compulsory module, only 15% of Masters students agreed. There was no clear consensus on how or if RRI teaching should be assessed. Follow-up interviews suggested that students believed RRI should be taught in a seminar-style format with open discussions rather than a lecture style delivery. Building on this, 59% of students (29) said that they would like RRI to be taught by a member of staff specialized in their area of research/discipline. In the follow-up interviews, a respondent expressed concerns that if RRI were taught by member of staff specialized in RRI but without relevant scientific expertise the 'student will complain and not listen as they think it isn't directly relevant to their degree course'. With respect to perceived prerequisite knowledge, 59% of respondents felt that they had the relevant knowledge and skills when 10% did not and 31% were not sure.

Students who declared they received training in RRI provided valuable insights about their experiences of learning RRI. They described their RRI training as 'refreshing', 'enjoyable' and giving them 'quite a nice break from a heavy science area'. Several respondents noted that learning about RRI was 'different' to other aspects of their scientific training. RRI was indeed often perceived to be a 'fuzzy' concept, difficult to grasp and capture with overlapping areas ('the only challenge we met was understanding the AREA framework because a lot of those four sections overlap quite a lot'). Despite this, students commented on the benefits they associated with their RRI training, from developing their critical and reflective thinking skills to providing pathways for public engagement. Students who encountered RRI as part of their training also appeared better equipped to understand and articulate the relevance of RRI for their future career. One respondent interested in working in research highlighted how RRI training was critical for his future as '(funding bodies) are making RRI an important, valuable part of their funding'. Anticipating that RRI-related concerns will grow in the private sector, one respondent believed their RRI training made them 'more employable'.

COVID-19: a catalytic event for RRI training?

The final part of the survey sought to explore students' perceptions of the impact of the COVID-19 pandemic on the perceived desirability of RRI in their training and future

careers. The majority of participants (41 agreed, 4 did not, 4 were unsure) agreed that 'people will be more interested in the role of science in society' as a result of the COVID-19 pandemic, with 39 agreeing (5 disagreed, 9 were unsure) that 'people will value scientific advice more when thinking about other societal challenges, such as climate change'. The majority of participants (34 agreed, 8 disagreed, 7 were unsure) also perceived that, in the aftermath of COVID-19 crisis, scientists would be required to consider social responsibility further when carrying out research.

A majority of participants (41) felt that the COVID-19 pandemic made RRI more relevant for science. Whilst 39 agreed that, as a result of the COVID-19 pandemic, RRI became more relevant to them as a scientist, only 29 saw RRI as more relevant to their future career (28 participants agreed that training in RRI could make them more employable whilst 8 disagreeing and 13 being were unsure). Students who had received RRI training as part of their studies, particularly those interested in pursuing academic research careers, believed their RRI knowledge enhanced employability as many funding bodies 'are making RRI an important, valuable part of their funding' (see above). In addition to this, one participant anticipated that the COVID-19 crisis was likely to generate a more anxious research/scientific climate in which 'you just have to be more careful'. This thought was echoed by a fellow respondent:

> Given the nature of COVID-19, scientific research, especially in the field of vaccination development, has been heavily spotlighted. Scientific research is very much a hidden field for the general public. In the case of a global pandemic, relating to diseases, the scientific community has to be prepared to inform the general public, so they are well educated on the process of scientific research and the realistic timescale/expectation of successful results. RRI would hopefully allow us to be well equipped for increased spotlight from the general public and media, if another event, like the COVID-19 epidemic was to happen again.

In contrast to this, a student believed that it was the skills developed (e.g.: thinking transversally, broadly, critically) as part of the training that would best support their employability, more than the knowledge gained. On the other hand, students who regarded RRI training as an asset for employment mobilized explanations extrinsic to RRI training itself. For example, a Chinese respondent planning to start work in China did not anticipate that they would encounter 'too many bosses who will consider RRI': '(In China) there is a big gap between scientific research and social needs, which means RRI will not be as useful as in Western countries'. As mentioned above, data suggest that students' cultural background and their plans for the future shape and inform their engagement with RRI as well as their perception of its importance for their future.

Conclusions and recommendations

The emergence of RRI over the past decade or so has coincided with an increased interest in SDGs, EDIA, and global challenges. The translation of RRI from concepts to its practical implementation in the STEM sector (in both academia and industry) has involved an evolution of the definitions of RRI, a recognition of the need to move RRI discussions further upstream in HE training, and a need for change in cultural norms and philosophies.

Based on a student-led mixed methods study, the findings reported in this paper point to the importance of individual characteristics and cultural backgrounds in shaping students'

engagement with RRI, as well as the significance of different student learning contexts for their engagement with RRI. These observations have important implications for the learning and teaching of RRI in scientific training, especially within HE. We propose below a student-centred learning and teaching approach to RRI training in STEM HE, which we hope will inform and guide RRI pedagogy in HE contexts, specifically when training the next generation of STEM scientists.

Reflexive, relevant and interactive

As the study shows, attitudes toward RRI and exposure to RRI principles are heavily influenced by cultural backgrounds and social contexts within which students have been immersed. Educators should not assume that the value and benefits of RRI principles are self-evident, self-explanatory and uncontested. Whilst they may be readily accepted by some learners, they may warrant discussion for others. Learners' receptivity cannot be assumed but ought to be built and negotiated. Moreover, RRI may assume different meanings in different contexts and/or some dimensions of social responsibility may be prioritised over others. Exploring competing definitions of RRI, the evolution of RRI principles and their implementation in a range of contexts are important to develop a shared understanding among students as well as foster reflexivity and interactivity (presuming an acknowledgement of the intersectional nature of the Other), two core principles of RRI. This is particularly important given the internationalisation of higher education, with students arriving from a variety of backgrounds and contexts in which RRI may not be taught and/or have achieved a formalised central position in scientific enquiry. Educators/trainers need to be mindful of how students' backgrounds, cultures, past training and experiences, as well as their hopes for the future, affect meaningful engagement in RRI training. The opportunity for student voice in the progression of training should also be a deliberate component (e.g. through creating a safe space for honest, critical and constructive discussion of the issues that arise).

In light of the findings of the present study, we argue for a 'blank state' approach to teaching RRI to early PG students with built-in flexibility to explore and capitalise on prior knowledge, which will show how RRI training is relevant to the whole cohort of students. Our study of students who are at different educational stages shows that for effective RRI training the level of engagement and discussion should be adapted to their respective stages of learning. We suggest that no assumptions should be made about levels of pre-existing RRI knowledge, a consideration that could change if some RRI training were to appear in UG level courses for example, focusing on awareness raising and general provision. Comprehensive and applied knowledge of RRI would then be accessible at early PG level, perhaps in the context of a specific research project. Highlighting to students how RRI training can help them develop responsible researcher skills, which includes meeting regulatory requirements around traceability, openness, record-keeping, and accountability, is key to motivating students and helping them to grasp the immediate importance and relevance of RRI; this will hopefully form the basis of a more holistic long-term engagement with RRI beyond academia. On a more instrumental yet significant level, RRI training supports students' career readiness and should also be acknowledged as such in RRI training. The increase in the significance of RRI (with RRI terms, concepts and frameworks coming into use, and the encouragement of responsible research by funding/regulatory bodies) is likely to result

in a rise in RRI-related career opportunities in the future. Three specific areas that might be anticipated to increasingly provide career opportunities are multi-stakeholder engagement/participation, outreach, and EDIA.

Engaging with reflective practice, which in the UK is integrated within the AREA framework, has been identified as a potential challenge for many STEM students. Although these students engage in reflective practice as individuals, citizens, and learners, they may not regard reflexivity as a 'legitimate' method of enquiry in the context of their studies. This would need to be factored into RRI training that is tailored for STEM students, so they have the means and confidence to access the RRI curriculum. RRI provision should be interactive, making students interrogate and critically examine beliefs and values in a reflective, discursive, and open-ended manner. As the study suggests, fostering reflective practice requires both safe and interactive spaces for students to explore their ideas. Favouring face-to-face, interactive, small group teaching and learning activities is a good strategy to embed and develop reflective practice. Students can discuss key concepts and examples between themselves, with diverse cohorts of students bringing a range of sensibilities and perspectives to the discussions. As our study suggests, using real-life case studies can ground students' learning and bring out RRI's relevance to real-world problems. The COVID-19 pandemic was one such real-world problem. Recognizing the value of situated learning approaches in RRI training, we suggest that because of its global nature, the recent COVID-19 crisis provides a shared context and a situated case study through which students can reflect on the impact of scientific innovation on society but also some of the challenges associated with it. Students overwhelmingly identified the pandemic as increasing the relevance of RRI even though the time period covered by the survey was largely before the development of the mRNA vaccines and the widespread use of lateral flow testing in the UK.

Finally, as RRI grows in significance in the STEM sector, it appears key for future scientists to embed RRI in their scientific training from the onset, forming the basis for life-long learning and reflexivity in their scientific practice. Whilst the provision for RRI training is growing, many existing research staff in HE and industry have currently limited awareness of RRI. Trained students should be supported to be agents of change, able to pass their RRI knowledge and reflections to both senior and junior co-workers in the academe and beyond. Students/employees trained in RRI can also foster cross-sectional and interdisciplinary dialogue between colleagues and researchers (who may come from sectors with established RRI traditions), as well as impart their own knowledge and awareness directly to their colleagues. Ultimately, striving for best practice in the learning and teaching of RRI is paramount, for the manner in which it is imparted will keep its principles agile, allowing RRI to remain relevant and reflect societal values as well as advances in scientific knowledge and practice.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the EPSRC (EPSRC Centre for Doctoral Training in Advanced Biomedical Materials, SJW and AGH, Grant number EP/S022201/1 and Molecular Robotics, SJW, Grant number EP/P027067/1).

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