Knowledge Exchange

The art of publishing reproducible research outputs

Supporting emerging practices through cultural and technological innovation

Publication date: November 2021

DFG CSC Jisc cnrs SURF DeiC

Acknowledgments

This study was underpinned by the work of the KE Task and Finish Group on publishing reproducible research output, led by Juliane Kant and Anna Mette Morthorst as KE Group leads and Birgit Schmidt and Jeroen Sondervan as expert leads:

- Anna Mette Morthorst (Danish e-infrastructure cooperation (DeiC)
- Birgit Schmidt (University of Göttingen)
- Birte Christensen-Dalsgaard (Aarhus University)
- Daniel Nüst (University of Münster)
- Jeroen Sondervan (Utrecht University)
- Juliane Kant (Deutsche Forschungsgemeinschaft (DFG))
- Matt Jaquiery (University of Oxford)
- Pierre-Carl Langlais (Paris Sorbonne-CELSA)
- Saskia Woutersen (Leiden University)
- Verena Heise (Independent Open Science researcher, trainer and consultant)
- Yrsa Neuman (Åbo Akademi University)

We also gratefully acknowledge the support from Bas Cordewener and Sarah James (Knowledge Exchange Office), and the work of Laura Fortunato (University of Oxford), who provided a critical review of our research and helped us in navigating the complexities of this evolving area. Finally, we record our appreciation to the 51 contributors without which this study would not have been possible, for their valuable insights and for their time during a particularly turbulent period. A full list of project stakeholders is available in Appendix A.

Report cover image: The Alchemist, 1663, Cornelis Bega. Courtesy National Gallery of Art, Washington.

Title: The Art of Publishing Reproducible Research Outputs: Supporting emerging practices through cultural and technological innovation.

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DOI: https://doi.org/10.5281/zenodo.5521077

Executive summary

Introduction

Background and objectives

Knowledge Exchange (KE) (knowledge-exchange.info) has commissioned the present report to explore **current practices and barriers in the area of research reproducibility, with a focus on the publication and dissemination stage.** Our findings seek to compare and inspire strategies, policies and operational practice and share lessons learned from a wide range of stakeholder groups.

Definitions

In this work, we define research reproducibility **as cases where data and procedures shared by the authors of a study are used to obtain the same results as in their original work.** We acknowledge that other concepts such as replication, robustness and the generalisation of research findings are relevant to the discussion, but we considered these to be beyond the formal scope of our research.

Methodology

In this report, we captured the views of research funding organisations, research performing organisations, learned societies, researchers, academic publishers and infrastructure and service providers from around the world. **We applied the Knowledge Exchange Open Scholarship Framework (KE OS Framework) (knowledge-exchange.info/event/os-framework) – a model to address specific aspects within open science – to investigate reproducible publication practices:** this informed the design and delivery of all components of our research, including a comprehensive literature review and a series of **interviews and focus groups with a total of 51 contributors**. Interview and focus group findings were transcribed and qualitatively coded for thematic analysis.

Framing the research reproducibility discourse

Reproducible practices can take advantage of today's rapidly growing infrastructures

The growth of digital technologies has led to significant transformation across the research landscape, including new tools and services, novel research approaches and the proliferation of interconnected technical infrastructures. In this context, **a variety of options to document, share and analyse data and findings have become more widely available than ever before, fully opening the doors to reproducible workflows and publication practices.** The key benefits of reproducible research include increased confidence in findings and results and an ability to continue one's (or someone else's) work in the future. At the system level, reproducible research practices can lead to higher transparency, openness and trust in science.

Some barriers can hinder reproducible practices

Some barriers may hinder the publication of reproducible research outputs, including **current incentive structures in academia, differences in the technical capabilities of researchers, limited connectivity between technical solutions, and inconsistent reporting standards. Research methods, which tend to vary based on academic disciplines, also affect the effort to make one's work reproducible.** For example, research methods typically associated with quantitative disciplines are relatively straightforward to set up in a reproducible way. On the other hand, reproducible workflows become more complex to implement when a significant qualitative element is present.

Stakeholders, roles and responsibilities

Micro level: Researchers and research groups have direct control over everyday practices

Individual researchers and research groups have an important role to play, because they are responsible for designing, delivering and disseminating research and are the only ones with easy access to all the research objects involved. They can support reproducible publication practices by fostering and applying reproducible workflows and by considering any reproducibility requirements when they act as peer reviewers.

Meso level: Disciplines should communicate their requirements, and publishers should implement them

Research communities and disciplines can influence future policy development by defining and communicating their approaches to reproducibility to other stakeholders such as publishers, who do not wish to impose top-down requirements that may not mirror disciplinary practices. Once requirements are clear, **publishers can help by mandating the use of appropriate checklists or guidelines for editors, peer reviewers and authors** to encourage reproducible practices.

Meso level: Research performing organisations do not tend to mandate reproducible publication practices

Many research performing organisations do not have dedicated policies focusing on research reproducibility. However, they tend to make significant investments in cases where funder or policy mandates are introduced: since reproducible research practices are currently not a firm requirement, it is likely that research performing organisations will address research reproducibility via ad-hoc approaches according to their individual strategies and researcher bases.

Macro level: Research funding organisations see reproducibility as part of a broader discussion

Few research funding organisations are prominent in the research reproducibility landscape. Reproducibility is often discussed under broader requirements such as those around research data, open science or research integrity. Similarly to publishers, research funding organisations feel that it is difficult to set reproducibility requirements for grantees across a range of disciplines, and there is a limited sense of urgency to develop new policies.

Incentivising and enabling reproducible publication practices

Current incentives and support for reproducible publication practices are limited

Reproducibility efforts are not currently incentivised within the research process, and reproducible publication practices are commonly perceived as additional, unrewarded activities. Systematic efforts to reconsider current academic incentive structures are needed to more consistently reward behaviours that are conducive to reproducible publication practices. **The support of research performing organisations can be instrumental in relieving some of the time pressures on individual researchers and complement their skills where lacking.** This type of support can take the shape of new institutional roles such as data stewards, data curators or subject librarians.

New training and support pathways are developing across the world

A range of support and training pathways, both within and beyond research performing organisations, are developing worldwide. However, more structured support for reproducible publication practices would be welcome, as these initiatives are the exception rather than the rule. The role of champions was noted as an important awareness-raising mechanism, and interviewees highlighted that **there is scope to improve the provision of reproducibility training in student curricula.**

Technological innovation

Many digital infrastructures for reproducible publication practices are already available

A wide range of digital tools and infrastructures are available in today's research landscape, and researchers are generally aware of how these can be leveraged to implement reproducible publication practices. However, not all researchers are equally trained to use these tools (often in line with disciplinary customs and typical research approaches), and the lack of interoperability between infrastructures is seen as a practical obstacle.

FAIR data principles can support reproducible publication practices

The issues described around service connectivity are partly enshrined in the 'I' of the FAIR data principles – Findability, Accessibility, Interoperability and Reusability. More broadly, **FAIR data principles enable reproducible publication, as many of the practices underpinning data curation, sharing and reuse also support reproducibility.**

Covering the costs of reproducible publication practices

The cost of reproducibility checks varies based on timing and responsibilities

Funding the time and other related costs of reproducibility efforts is a key consideration for the future, and many stakeholders have a role to play in ensuring this is possible. Our research highlighted that **different types of costs may need to be covered: the time and efforts of researchers in the context of a research project; the time and effort of research support staff based at research performing organisations; reproducibility checks in the context of the publication process; and post-hoc reproducibility checks.** The first of these is seen as a necessary condition to move research reproducibility up the agenda, while the others currently are the subject of further discussion and experimentation.

Three main pathways are available to fund the cost of reproducibility checks

In the context of the publication process, we have identified three pathways to implement reproducibility checks. We found that **there is scope for publishers to establish in-house roles, such as data or reproducibility editors, and that third party providers could play a role in testing articles for reproducibility. In addition, peer reviewers may take on additional responsibilities by testing articles,** data, and code for reproducibility when these are being considered for publication; however, we note that the research community may be reluctant to consider this approach, as it requires time and expertise that not all researchers might have.

Funding for digital infrastructures can be beneficial to pilot new solutions

Our research found that two areas of digital infrastructures may benefit from increased or new funding to better support reproducible publication practices. First, since an increase in open research practices and sharing will require improved features and capabilities, **funding may help in extending the role of existing infrastructures.** Second, **public funding may be considered as a means to develop and pilot early-stage digital infrastructures** providing reproducibility-related functionality across the research process, with a view to develop sustainable business models in the medium-to-long term.

Monitoring compliance is complex in practice

Several complexities emerge when it comes to monitoring compliance with reproducibility requirements. Particularly, **it is difficult to reach an agreement around where the responsibility for conducting reproducibility checks should lie.** This is partly because such an activity includes the review of connected research objects, which, in turn, might require an understanding of (sub)disciplinary standards, methodologies, or subject matter that not all stakeholders are well equipped to monitor and/or enforce.

Conclusions

Reproducibility is part of the vision for open science

Reproducible publication practices are evolving as part of a broad process of cultural change in the research landscape. As a result, progress is slow and sustained over a considerable period of time. On the other hand, technological innovation is moving fast: the imbalance between technical and cultural innovation paints a complex but optimistic picture for the future of reproducible research. **The vast majority of researchers hold themselves to high standards: we expect that they will readily adopt reproducible publication practices, as long as a balance is found between increasing expectations and practical rewards.**

Diversity will be key in driving positive change

It is essential that the focus on reproducibility does not lead to a "shame and blame culture", but instead is welcomed as an opportunity to improve research practices. There is a risk for policies and their enforcement to leave little room for nuance. For some epistemic cultures, reproducibility will be harder to understand and implement, or perhaps is not even the goal; in others, reproducibility may not be seen as the key quality hallmark, but just as an option among many. **It will therefore be necessary to prioritise diversity as we rethink research practices to preserve and boost trust in science.**

Five take-away messages

Reproducibility is part of the vision for open science, alongside concepts such as replication, robustness and the generalisation of research findings. It is difficult to pursue culture change with regard to reproducibility without considering this broader context.

Stakeholder collaboration is needed to continue developing reproducible publication practices. All players from the individual researcher to national and international bodies have a role to play, including in the context of policy development and implementation.

Incentives for reproducible publication practices are currently limited. Research performing organisations are beginning to support researchers in meeting their growing reproducibility expectations, and there is increasing demand for new training and support pathways in this area.

The management, curation and sharing of research data and methods are necessary conditions for reproducible publication. It is essential for these practices to become the norm to push the reproducibility agenda forward, and some dedicated institutional roles such as data stewards may be required to keep up with the demand for support.

Reproducible publication practices require a range of technological solutions, but most contributors agreed that these are already available in today's research landscape. The key technical gap appears to be the interoperability between available tools and workflows; however, we also note that technological solutions for reproducibility are not currently covered as part of training curricula.

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1. Introduction

This work was commissioned by Knowledge Exchange, a group of national organisations from six European countries working to enable open science by supporting an information infrastructure on an international level. In this study, we seek to investigate current practices and barriers in the publication of reproducible research outputs and to determine how technical and social infrastructures can support future developments in this area.

Background and objectives

The proliferation of digital tools in today's research landscape has brought more opportunities than ever to document and open up the research process and its outcomes.[1] At the same time, research cultures have been shifting towards a desire for more transparency, including within the open science[2] agenda and current trends in scholarly communication. In particular, the ability to reproduce results in order to confirm their reliability is evolving to become a more established part of the research process: there is agreement that reproducible research practices can enable continuous scientific development and help guarantee the quality of published results.

Knowledge Exchange (KE) has therefore initiated an activity entitled "Publishing Reproducible Research Output", to explore current practices and barriers in this area, and to determine how technical and social infrastructure can support future developments. This report is part of KE's broader work on research infrastructures, open science and open access: it seeks to compare and inspire strategies, policies and operational practice and share lessons learned from a wide range of stakeholder groups.

Definitions

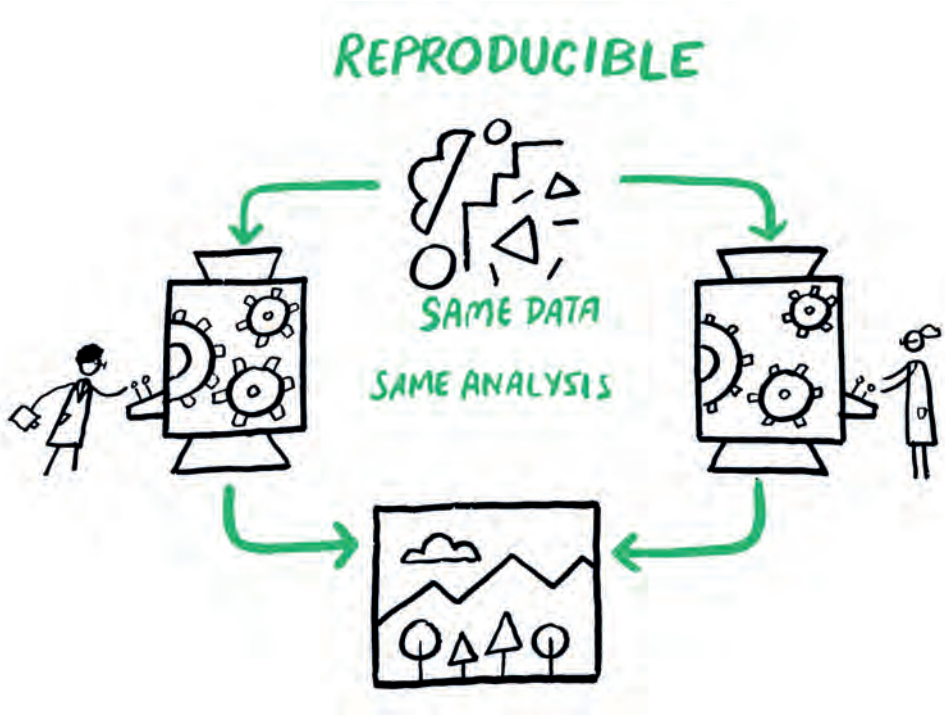
We acknowledge that "reproducibility, at least in many research disciplines and cultures, is one of the pillars of responsible research practices",[3] and is often associated with the neighbouring concept of 'replicability'. In this report, research reproducibility is defined as cases where **data and procedures shared by the authors of a study are used to obtain the same results as in their original work** (see **Figure 1**). This may require, for example, a detailed description of the methods used to process and analyse the data, access to any relevant datasets and an ability to obtain and run computer code, where appropriate.

1 Breuer, C., & Trilcke, P. (2021). Expanding academic publishing practices alongside the digital turn. Alliance of Science Organisations. 1-15. **https://doi.org/10.48440/ALLIANZOA.042**

2 In this report we use the term 'open science' in a broad sense, to denote open research/open scholarship and research communications regardless of discipline.

3 Tijdink, J. K., Horbach, S. P. J. M., Nuijten, M. B., & O'Neill, G. (2021). Towards a Research Agenda for Promoting Responsible Research Practices. Journal of Empirical Research on Human Research Ethics, 16(4), 450–460. **https://doi.org/10.1177/15562646211018916**

Figure 1. Our definition of reproducibility CC BY The turing way community; scriberia)[4]



On the other hand, we take the view that replication targets the validity of research, as new data is collected and, sometimes new analyses are conducted to check if consistent results can be obtained compared to the study under consideration. This and other related considerations, such as the robustness and generalisation of research findings have not been at the core of our research, but are mentioned throughout the report where relevant to the discussion.

4 The Turing Way Community., & Scriberia. (2021). Illustrations from the Turing Way book dashes. Zenodo. https://doi.org/10.5281/ZENODO.4906004

Methodology

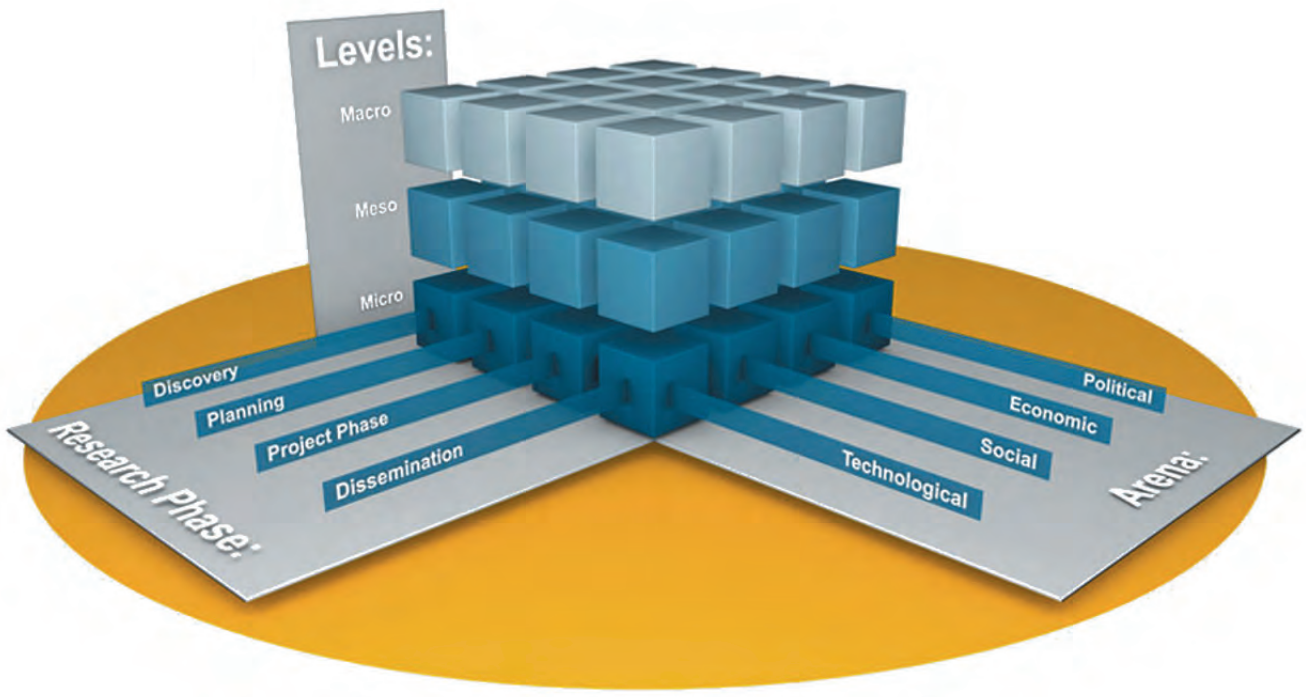
This study applies the Knowledge Exchange Open Scholarship Framework (abbreviated as: KE OS Framework) – a model to address specific aspects within open science – to investigate reproducible publication practices (see Figure 2). The KE OS Framework comprises three Levels (Micro, Meso, Macro), four Research Phases (Discovery, Planning, Project Phase, Dissemination) and four Arenas (Political, Economic, Social, Technological).

The above dimensions have been used to inform the design and delivery of a comprehensive literature review, a series of interviews with 41 stakeholders across the research landscape and two focus groups, capturing the views of a further ten stakeholders. Interview and focus group findings were transcribed and qualitatively coded for the purposes of thematic analysis.

The stakeholder groups considered included research funding organisations, research performing organisations, learned societies, researchers (both established and early-career), academic publishers and infrastructure and service providers. Our engagement activities prioritised capturing the views of stakeholders in countries represented in the Knowledge Exchange initiative i.e., Denmark, Finland, France, Germany, the Netherlands and the United Kingdom. Over the course of this work, we also engaged with stakeholders in other countries in Europe and from North America.

Finally, our study included an analysis of Twitter data focusing on a range of hashtags developed in collaboration with the KE Task and Finish Group. A detailed methodology for this is available in the form of an R notebook (see supporting data), and specific insights are included throughout the report.

Figure 2. The knowledge exchange open scholarship framework[5]



5 Knowledge Exchange. (2017). Open Scholarship Framework. https://bit.ly/30L9Sqv

Limitations

We recognise that the present study is subject to the following limitations:

- Study participants were recruited via convenience sampling, that is, we interviewed stakeholders who were both available and willing to participate
- Our stakeholder engagement activities focused on a range of specific countries. Therefore, it may not be appropriate to generalise the findings of this study to research cultures and contexts that were not consulted
- Our analysis is underpinned by thematic coding, which relies on an extent of subjective interpretation. The research data and its analysis have been openly shared to ensure that our underpinning evidence is available to any interested parties
- Social media data is a snapshot at a given point in time, and we note that Twitter does not offer a representative cut of the general population, nor does it allow us to draw definitive conclusions

Structure of the report

After this introduction, our report is structured as follows:

- Framing the research reproducibility discourse
- Stakeholders, roles and responsibilities
- Incentivising and supporting reproducible publication practices
- Technological innovation
- Covering the costs of reproducible publication practices
- Conclusions

All sections were informed by findings from both our literature review and stakeholder engagement activities. Quotes and case studies are provided throughout to exemplify the statements made in the report and ground them in the evidence gathered.

Supporting data

The following additional information has been made available over the course of this project, in the interest of enhancing the transparency and reproducibility of our work:

- Data management plan[6]
- Literature sources and thematic coding[7]
- Literature review slide deck (Interim report)[8]
- List of interviewees and interview questions[9]
- Anonymised interview coding summaries from NVivo[10]
- R Notebook and data supporting social media analysis[11]

Elements of this study involving human participants have received research ethics approval from the School of Anthropology and Museum Ethnography Research Ethics Committee (SAME REC) at the University of Oxford (Reference number: SAME_C1A_21_018).[12]

6 Loffreda, L., & Chiarelli, A. (2021). Publishing Reproducible Research Outputs - Data Management Plan. Zenodo. **https://doi.org/10.5281/ZENODO.4697399**

7 Loffreda, L., & Chiarelli, A. (2021). Publishing Reproducible Research Outputs - Literature sources and Thematic coding (Version 1) [Data set]. Zenodo. **https://doi.org/10.5281/ZENODO.4748748**

8 Chiarelli, A., Loffreda, L., & Johnson, R. (2021). Publishing Reproducible Research Outputs - Literature findings. Zenodo. **https://doi.org/10.5281/ZENODO.4675457**

9 Chiarelli, A., & Loffreda, L. (2021). Publishing Reproducible Research Outputs - Interviewees and interview questions (Version 1) [Data set]. Zenodo. **https://doi.org/10.5281/ZENODO.5141665**

10 Loffreda, L. & Chiarelli, A. (2021). Publishing Reproducible Research Outputs - Thematic coding of interview findings (Version 1) [Data set]. Zenodo. **https://doi.org/10.5281/zenodo.5512420**

11 Chiarelli, A. (2021). Publishing Reproducible Research Outputs - Text and data mining code (Version 2) [Computer software]. Zenodo. **https://doi.org/10.5281/ZENODO.5512019**

12 The use of the University of Oxford's Research Ethics Committee was facilitated by Laura Fortunato, who supported this research as a critical advisor.

2. Framing the research reproducibility discourse

The growth of digital technologies has led to a range of options to document, share and analyse research methodologies, research data and research findings more widely than ever before: these can be adopted by the research community to achieve increased transparency and sharing as well as to facilitate the future reuse of methodologies, data and findings. Some cultural and practical barriers remain, including the fact that the effort of reproducible workflows tends to vary by research method and discipline.

Understanding the focus on research reproducibility

The concept of research reproducibility has long been known and discussed in academia[13,14] as it is a core part of what we know as good research practice.

Over time, peer review has become the main pathway to verify that someone else's research has been carried out to a high standard and in line with key disciplinary customs and methodologies. However, starting from the advent of modern computers and symbolic languages (e.g. Fortran in the 1950s), many disciplines were "sent into warp speed",[15] with the range of options to document, share and analyse data and findings significantly increasing. Notably, this digital turn has not only affected traditionally computational and quantitative research, but also changed the shape of many qualitative disciplines, including activities such as thematic coding, digitisation of documents, annotations and recordings.

In addition, new and interconnected research infrastructures continue to emerge,[16] while, over the past ten years, "longstanding scholarly publishers have been metamorphosising before our eyes, shedding old ways of doing business and taking up broad initiatives to reinvent what publishers do and why they matter."[17]

> *"The traditional, two-dimensional article is no longer enough. These days you'd like to have dynamic plots, interactive plots, maybe even interactive data when you actually sift through the thing."*
> *Publisher*

13 Popper, K. (2005; originally published in 1934). The logic of scientific discovery. Routledge.
14 Dewald, W. G., Thursby, J. G., & Anderson, R. G. (1986). Replication in empirical economics: The journal of money, credit and banking project. The American Economic Review, 76(4), 587-603. https://bit.ly/3lVUnnN
15 Perkel, J. M. (2021). Ten computer codes that transformed science. Nature, 589(7842), 344–348. https://doi.org/10.1038/d41586-021-00075-2
16 European Strategy Forum on Research Infrastructures (ESFRI). (2021). ESFRI announces new RIs for Roadmap 2021. https://bit.ly/3vsA3NQ
17 The Scholarly Kitchen. (2021). Digital Transformation Requires Cultural Evolution. https://bit.ly/3A3DZ8F

Today's digital way of working and the range of ways to share and connect (digital) research objects can enable reproducibility to become a reality in a way that has not been possible before. In this section, we explore the key drivers and barriers in the context of research reproducibility, setting the scene for the more detailed discussion presented in the remainder of our report.

The challenges in defining reproducibility

Both the academic literature and our research find that, while reproducibility is an issue that transcends disciplinary boundaries, the range of terms and interpretations across the board are inconsistent and at varying levels of maturity. This is unsurprising, as the discourse in this area has developed as a bottom-up movement in different communities. The fractured landscape of research reproducibility makes communication more difficult; it also means that efforts may be less effective than ideal due to confusion and an apparent lack of common ground between disciplines.

> *"[Confusion around definitions] certainly creates friction in the sense of slowing down people understanding what each other means, and so there are a lot of terminologies that get generated making it seem like it's more complicated than it is… that just makes it harder for people to talk to each other."*
> *Infrastructure provider*

In this study, we considered research reproducibility as cases where data and procedures shared by the authors of a study are used to obtain the same results as in their original work. This definition, alongside our specific interest in the publishing and dissemination phase in the research process, meant that contributors could immediately grasp our area of focus and terminology. Some contributors pointed out the benefits of having a practical and specific definition of reproducibility, as this is:

- Helpful in **awareness raising** and **teaching** efforts
- Makes the concept more **understandable** and any problems easier to tackle

However, many conversations also highlighted that inclusivity is key, and that too narrow a definition will cause disengagement in some disciplines. In particular, our definition resonates more with the quantitative sciences than the qualitative ones, chiefly because the latter may leverage a range of methodologies that rely significantly on individual judgement and interpretation. In these cases, the concepts of 'data' and 'analysis' are more nuanced, and there is some resistance to one-size-fits-all definitions in this field of research.

> *"Most people in [qualitative] fields would not feel that [the definition of reproducibility] was relevant to them, because the analytical process is one that is to some extent inherently subjective. So, the whole concept of reproducibility via that definition is one that they just don't feel is relevant to them, rightly or wrongly."*
> *Researcher*

In addition, some noted that it is difficult to separate reproducibility from replication, robustness and generalisation of research findings. Particularly, it is possible to study these concepts separately in terms of infrastructures, requirements and policies, but there is a shared view that any meaningful change in research cultures will have to address these considerations (and more, e.g. openness, FAIR-ness,[18] ethics, integrity, rigour, transparency) in a concerted way.

> *"What does reproducibility mean, and aren't we really talking about research integrity and reliability here? If we tie ourselves into a particular definition of reproducibility – and we can get authors to do that – there would still be huge problems that were not addressed."*
> *Publisher*

An important point made by several contributors is that openness (e.g. data and code sharing, open access) are enablers of reproducibility, but do not necessarily guarantee it. For example, for research to be reproducible, all data and files have to be openly published but also clearly separated, labelled and documented, using automated

18 FAIR data are data which meet principles of Findability, Accessibility, Interoperability, and Reusability. See: Go Fair. (n.d.). Fair Principles. **https://bit.ly/3vrewFq**

approaches as much as practicable to (i) avoid manual intervention; and (ii) enhance standardisation.[19]

Although promoting best practices under the umbrella of openness and open science is indeed an important starting point, we highlight the difference between two key activities:

- **Sharing** research outputs, e.g., an article and the underpinning data, code, or software (if any) and detailed documented methodology
- **Evaluating and testing** these in terms of reproducibility of the findings.

This distinction clearly shows that roles and responsibilities (see **section 3**) are not obvious when it comes to reproducible publication practices: for example, researchers may work to ensure that their own results are reproducible but also check someone else's articles (e.g. as peer reviewers or data/code reusers).

> *"If you share protocol and data and both are fully open, then you might still not be able to reproduce the study… You can't put everything in writing in a protocol, it's always a simplification of reality… There are limits to what can be shared, even if you do your best."*
> *Researcher*

Drivers and perceived benefits

In the last decade, some agreement has emerged that good research should be reproducible, and this is seen as a minimum requirement for science rather than as an abstract goal. Our study found that, generally speaking, it is not always easy to immediately recognise or experience the benefits of reproducible publication practices, but contributors agreed that further efforts in this direction are strategically important for the future of academia and to boost trust in research.

> *"I think if people are taught how to set up workflows that are reproducible, it also benefits them in the first place. If I have to touch the same project three years in the future, I might have forgotten what specifically I did, and if there is good documentation, everything is there and I save a lot of time."*
> *Researcher*

Of the researchers that contributed to this study, most are motivated to ensure that their work is reproducible by a personal belief that this is a fundamental feature of academic research. It is widely recognised, however, that the time investment required by reproducible publication practices is not yet commonly incentivised or rewarded: should this remain the case, reproducibility is likely to remain a limited practice and of interest to a small subset of motivated individuals (see **section 4**).

> *"I think there is an intrinsic incentive to want your work to be right. But at the moment, that would mean maybe doubling the time you spend on the work, and that is not incentivised."*
> *Researcher*

"Five selfish reasons to work reproducibly" have been hypothesised in the literature,[20] and they resonate with the findings of our interviews and focus groups:

- Reproducibility helps to "avoid disaster": transparent and open research workflows can help researchers avoid impactful data analysis and interpretation errors, both before and after article submission
- Reproducibility makes it easier to write papers: a well-documented research workflow means that writing about it will be easier, as there will be enhanced confidence that numbers, figures and tables are fully up to date

19 Fortunato, L., & Galassi, M. (2021). The case for free and open source software in research and scholarship. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 379(2197). https://doi.org/10.1098/rsta.2020.0079

20 Markowetz, F. (2015). Five selfish reasons to work reproducibly. Genome Biology, 16(1). https://doi.org/10.1186/s13059-015-0850-7

- Reproducibility helps reviewers see things the author's way: by having access to a range of research objects, peer reviewers can fully understand what authors have done, leading to a better appreciation of the results and conclusions of a study

- Reproducibility enables continuity of one's work: good documentation on both methods and research data/code is expected to stand the test of time and will help authors and reusers alike in building on published results

- Reproducibility helps to build one's reputation: while there are few concrete examples of this, there is an emerging perception that publishing reproducible research can earn researchers recognition within some disciplinary communities

Importantly, the perceived benefits listed above apply at the level of individual researcher, but their potential positive impact extends much farther: the availability of open and/or FAIR research objects, including detailed documentation, can open the doors to new and unexpected research that authors had not considered in the first place.[21,22] This includes the use of emerging techniques requiring large amounts of data as an input, such as artificial intelligence and machine learning, which build on the fact that "the science system is in "landslide transition from data-sparse to data-saturated."[23]

> *"If you work reproducibly, and others in your field take that data and show that you are working reproducibly, they're going to trust your data more. That may result in collaboration offers, it may result in people reusing your data more often than somebody else's data… in which case that will result in more citations."*
> *Research performing organisation*

Potential barriers

Our work shed light on a range of key barriers to the publication of reproducible research outputs (see **Table 1**).

Table 1. Key barriers to reproducible publication practices.

Rewards and incentives
▸ Current incentives are not conducive to reproducible research
▸ Current evaluative metrics focus on quantity and impact rather than on quality and reproducibility
Publishing and reporting standards
▸ Sharing code, data and methods is not mandatory
▸ Methods are not sufficiently detailed, including because of limitations on word/page counts
▸ Reporting standards for authors and peer reviewers are lacking or inconsistent, including across disciplines
Technical and analytical skills
▸ Training and mentoring are limited, including in computing analysis, coding and novel techniques
▸ Not all researchers are equally familiar with or competent in computing and software for reproducibility
Technical infrastructure
▸ There is limited connectivity between scholarly communication infrastructure and researcher workflows and tools
▸ Collaboration and communication between research repositories and between repositories and journals is not yet well-developed. Neither are tools enabling the connection of research objects
Practical and cultural barriers
▸ Some authors may be unwilling (i.e. an individual position) or unable (e.g. practical or legal obstacles) to share data for a wide range of reasons, including data ownership, sensitivity, ethics and confidentiality, intellectual property or fears of misuse

21 European Commission. (n.d.). Facts and Figures for Open Research Data. **https://bit.ly/3owoHa9**
22 Department for Business, Energy & Industrial Strategy. (2019). Realising the potential: Final report of the Open Research Data Task Force. **https://bit.ly/3l6wN7d**
23 Burgelman, J. C., Pascu, C., Szkuta, K., Von Schomberg, R., Karalopoulos, A., Repanas, K., & Schouppe, M. (2019). Open Science, Open Data, and Open Scholarship: European Policies to Make Science Fit for the Twenty-First Century. Frontiers in Big Data, 2(43), 1-6. **https://doi.org/10.3389/fdata.2019.00043**

Although researchers are generally aware of existing expectations around research quality and open research practices, they have competing priorities and little time and incentives to focus on reproducible research workflows. Academic interviewees highlighted that, while the benefits of investing in reproducible practices are valued and understood, their establishment is slowed down by the "publish or perish" culture, in which scholars are under pressure to publish in scholarly journals regularly in order to progress in their academic careers. This often forces researchers to prioritise fast(er) publication, which can result in limited (or no) data sharing and in turn undermine the reproducibility of published work.

> *"The main barrier right now is probably time constraints. Initially, it takes a lot of time to set up a workflow that is reproducible and to prepare the materials in the way that they make sense to other people and are shareable. From personal experience, this is a time investment."*
> *Researcher*

Unsurprisingly, our interviews also showed that published articles continue to be the most highly rewarded of research outputs, which only exacerbates the concerns in **Table 1**. Initiatives to address this concern are, indeed, under development, and we cover this in more detail in **section 4**.

> *"Incentives in research hang on the published article. And so, the behaviour, the routine, over the last hundred years has been just to focus on getting that published article and then to move on. As long as that's allowed, I think our attempts to encourage reproducibility or to really enable and realise reproducibility across a huge segment of the literature is going to be limited."*
> *Publisher*

In practical terms, we found that researchers have different skill sets – often varying by discipline – when it comes to publishing reproducible research. These develop at varying paces across disciplines, commonly in response to the different methodological requirements present in one's field.

Uptake of digital tools and services underpinning reproducible publication practices varies widely, and our research suggests that researchers in quantitative disciplines appear most familiar with existing products as these are currently used in the research process. It should be noted that tools that, in principle, can enable reproducibility throughout the research process and at the time of publication may not always be used for these purposes: for example, GitHub can potentially underpin reproducible research workflows but is often used as a collaboration platform rather than to share and verify one's data and code at the time of publication alongside its repository integration via Zenodo.[24] In **section 5**, we explore a broader range of technologies that can support reproducible publication practices.

> *"If you do computational research, the tools are indeed out there, but they are also scattered and differently evolved per discipline… But for another type of study, for example in archaeology, it is much less structured how to do that in that sense. So, it is discipline-specific, but it's definitely evolving."*
> *Research performing organisation*

Challenges in relation to data sharing are particularly significant and have implications across the research lifecycle: a lack of (FAIR and, in many cases, open) data underlying analyses is a barrier to the execution of reproducibility checks and, more broadly, it impedes reuse. In some cases, sharing data is indeed complex, e.g., where ethical considerations play a role or where data is commercially sensitive (see **section 2**).

> *"Medical data has a lot more hurdles to manage. Some data in some disciplines just isn't possible to make available. Different fields are easier and harder to work with because of the dynamics of the types of materials that they work with."*
> *Publisher*

24 GitHub. (n.d.). Making your Code Citable. **https://bit.ly/2Z4Bneh**

The impact of disciplinary differences

Our discussion so far has only touched on the potential impact of disciplinary differences on a researcher's ability to implement reproducible research practices. Our literature review and interviews indicate that different challenges can arise based on (i) the research methods used; and (ii) a researcher's discipline (although the two are often closely related).

> *"Most of what I do is quantitative and randomised control trials, but I very much understand the pushback that I get from some of my colleagues when they talk about their qualitative research. It is extremely difficult to write up their work and preserve anonymity whilst still enabling transparency and allowing others to make the same inferences based on this data."*
> *Researcher*

We found that some empirical research methods better lend themselves to reproducible workflows,[25] such as software development and standardised or semi-standardised experiments. These are typical in quantitative disciplines, where research objects such as data tables are common and can be generated via semi or fully automated means for analysis, sharing, inspection and reuse.

On the other hand, reproducible workflows become more complex when a significant qualitative element is present, when research is not standardised, or when it is based on rare, unique, perishable or inaccessible materials: in these cases, more time will be required for data gathering, curation, documentation and/or sharing. For example, considerations such as data protection and ethics can play a role: a common hurdle is to "de-identify personal data while also [...] minimising the loss of richness of the information provided".[26]

> *"We have to walk a fine line in my field, because we deal with data from human volunteers and obviously, we de-identify as much as possible. For example, a brain scan can uniquely identify a person. So sometimes we deal with data that is inherently hard to anonymise."*
> *Learned society*

We acknowledge that the present section does not mention non-empirical methods that draw on personal observations, reflections on current events, and/or the authority or experience of the author.[27] In these cases, interviewees questioned whether research reproducibility is even desirable or applicable in the first place. Particularly, some contributors highlighted that a one-size-fits all approach to reproducibility is not appropriate and noted that it is essential to allow for diversity in research methods and disciplines when taking this discussion forward.

> *"A paper around religion or philosophy might not necessarily be evidence-based or have any specific data. The author might just be sharing their own new theory and do nothing to prove it or disprove it. So the meaning of 'reproducibility' may change or just be irrelevant in some cases."*
> *Infrastructure provider*

25 Penders, B., Holbrook, J., & de Rijcke, S. (2019). Rinse and Repeat: Understanding the Value of Replication across Different Ways of Knowing. Publications, 7(3), 52. **https://doi.org/10.3390/publications7030052**

26 Kurapati, S. & Teperek, M. (2019). What does reproducibility mean for qualitative research? **https://bit.ly/3iyrGev**

27 Dan, V. (2017). Empirical and Nonempirical Methods. The International Encyclopedia of Communication Research Methods. 1-3. **https://doi.org/10.1002/9781118901731.iecrm0083**

Case study: The data infrastructure investments of the Economic and Social Research Council (ESRC)

The ESRC, which is part of UK Research and Innovation, is the UK's largest publicly-funded organisation for funding research on economic and social issues, focusing on research with an impact on business, the public sector and civil society. One of their missions is to "develop and support the national data infrastructure that underpins high-quality research", and this is achieved, among other means, by funding a wide range of data infrastructures.

The ESRC has made significant investments in data infrastructures (e.g. Administrative Data Research UK, the UK Data Service, the Urban Big Data Centre and the Consumer Data Research Centre), and these all support facilities and technologies that safeguard identities and enable secure, controlled data access.

Infrastructures like the above are key to enable reproducible publication in all disciplines where concerns exist around data sensitivity and confidentiality for individuals and businesses alike. In the context of COVID-19, the UK Data Service has put in place additional measures (with the consent of data owners) to allow usage of their Secure Lab facilities from home. This demonstrates that, through innovation, there are options to support users to access sensitive and confidential data remotely that provide robust safeguarding. Another example is provided by Administrative Data Research UK, which has invested in **SafePods (https://bit.ly/3Dumpg5)** – a network of independent safe settings to support access to secure data.

More broadly, the ESRC also has data sharing requirements for their grantees, based on the recognition that "data are the main assets of economic and social research". This covers documentation and metadata to "provide secondary users with essential information to independently understand the data, enable discovery, and allow for scientific reuse" – behaviours that are highly conducive to reproducible research and publication practices.

Finally, we note the important role that funders can play by investing in dedicated infrastructures to support data users and promote positive behaviours with regard to reproducible publication practices: the UK Data Service ran the 'Love Your Code' event as part of the 2020 Love Data week, focusing on the exchange of information and knowledge around code sharing and its benefits.

3. Stakeholders, roles and responsibilities

Roles and responsibilities for reproducibility are complex, and stakeholder cooperation is essential. Individual researchers and research groups can support reproducible publication practices by adopting appropriate workflows, with support from their institutions and using growing research infrastructures. Research communities can help develop and communicate their customs to journals and research funding organisations, where policies, including at the publication stage, are currently developing.

Exploring roles and responsibilities

In the context of this project, we sought to discuss the roles and responsibilities of different actors when it comes to reproducible publication practices. A summary of our findings is presented in **Table 2**, and the most significant feature is the large extent of stakeholder collaboration required to deliver on the set of activities identified.

In this section, we explore the landscape of stakeholder relationships to provide insights into what stakeholders at the micro, meso and macro level (based on the KE OS Framework) could do to take the reproducibility discourse to the next level.

Micro level: Researchers and research groups

In our consultation, there was broad agreement that researchers have a key role to play when it comes to reproducible publication practices. This is simply because they are responsible for designing, delivering and disseminating research and are the only ones with easy access to (and detailed understanding of) all the research objects involved.

Individual researchers and research groups can support reproducible publication practices by fostering and applying reproducible workflows, including research data management, data and code gathering and curation, and the sharing of appropriate research objects alongside their articles.[28] They can also play a role when acting as peer reviewers, for example in cases where journals include reproducibility requirements (see below).

As discussed at the end of the present section, micro-level players can also play a key role in policy development: they are the only ones who can help meso- and macro-level stakeholders understand specific requirements arising in different disciplines and research contexts.

> *"Ideally, it's the authors' responsibility to make sure that their work is reproducible. And they should facilitate that. To a certain extent we are in a situation where authors are submitting their research and everybody's taking it on trust that the authors have done their job right."*
> *Publisher*

28 Turkyilmaz-van der Velden, Y., Dintzner, N., & Teperek, M. (2020). Reproducibility Starts from You Today. Patterns. 1(6). https://doi.org/10.1016/j.patter.2020.100099

Table 2. Possible roles and responsibilities in the publication of reproducible research outputs.

Level	Stakeholder	Detailed responsibilities arising from our consultation
Micro	Researchers and research groups	▸ Fostering and applying reproducible workflows, including data and code gathering and curation ▸ Sharing appropriate research objects (digital and physical) alongside publications ▸ Testing articles for reproducibility, when acting as peer reviewers (if appropriate, including because the current reward mechanisms do not encourage this)
Meso	Communities and disciplines	▸ Discussing, testing and refining disciplinary customs and standards for reproducible publication practices ▸ Communicating requirements for reproducible publication practices to higher-level stakeholders
	Learned societies	▸ Fostering discussion forums on reproducibility ▸ Providing discipline-specific training to meet the expectations of publishers and research funding organisations
	(Inter)national reproducibility networks	▸ Connecting the dots between peer-led discussions (which are relatively young and disconnected, across different disciplines) and other stakeholder groups ▸ Support collaboration across national boundaries ▸ Provide an extent of coordination in the broader context of open science practices
	Research performing organisations	▸ Setting policy expectations for staff (e.g. sharing of data objects, extent of checking required, disciplinary differences) in the broader context of open science practices ▸ Raising awareness of key requirements arising from policy expectations ▸ Providing support via an appropriate mix of data stewards, research object curators or subject librarians ▸ Providing general and discipline-specific training (for students and staff) to meet the expectations of publishers and research funding organisations ▸ Providing access to an appropriate mix of digital and physical infrastructure to underpin reproducible research workflows ▸ Providing funding for reproducibility-related tools during their start-up/pilot phase ▸ Developing and implementing reward mechanisms for reproducible publication practices in the broader context of open science practices
	Academic publishers and journals	▸ Setting policy expectations for authors (e.g. sharing of data objects, extent of checking required, disciplinary differences) in the broader context of open science practices ▸ Raising awareness of key requirements arising from policy expectations ▸ Developing and implementing reward mechanisms for reproducible publication practices ▸ Enforcing policy expectations, e.g. via author, editor and reviewer checklists/ guidelines/standards covering research reproducibility considerations ▸ Resourcing and training data or reproducibility editors with responsibilities for reproducibility checks of submitted or accepted manuscripts ▸ Engaging peer reviewers to set clear expectations around roles and responsibilities ▸ Working with infrastructure providers to implement practical solutions (e.g. journals to take up the use of Binder or Jupyter notebooks, where appropriate)

Level	Stakeholder	Detailed responsibilities arising from our consultation
	Infrastructure providers[29]	▸ Engaging a broader range of disciplines to develop a more inclusive set of tools and workflows (e.g. beyond computationally-focused disciplines) ▸ Delivering reproducibility checks in partnership with authors, publishers and research funding organisations ▸ Developing sustainable business models to serve the academic market, including with subsidisation from research funding and/or research performing organisations, where appropriate ▸ Working with publishers and journals to implement practical solutions (e.g. journals to take up the use of Binder or Jupyter notebooks, where appropriate)
Macro	Research funding organisations	▸ Supporting research communities in discussing, testing and refining specific requirements around research reproducibility (e.g. development of funding instruments to address this) ▸ Setting policy expectations for grantees (e.g. sharing of data objects, extent of checking required, disciplinary differences) in the broader context of open science practices ▸ Raising awareness of key requirements arising from policy expectations ▸ Developing and implementing reward mechanisms for reproducible publication practices ▸ Covering (some of) the costs of reproducible publication practices where these mirror policy expectations ▸ Monitoring and evaluating policy implementation ▸ Providing funding for reproducibility-related tools during their start-up/pilot phase
	Policymakers	▸ Setting policy expectations at the system level and coordinating national efforts in the broader context of open science practices ▸ Making publicly-funded digital and physical infrastructure a policy priority, to ensure long-term sustainability and avoid vendor lock-in

29 Note that infrastructure providers are discussed separately in **section 5**.

Meso level: Disciplinary customs

Our interviews highlighted a need for research communities and disciplines to own the development of requirements around reproducible publication practices. This is a key consideration, as our publisher and funder contributors shared their concerns around imposing top-down requirements that may not mirror disciplinary practices.

The development of disciplinary customs (including as part of efforts led by learned societies)[30,31,32] is a very powerful tool, as these effectively act as self-imposed policies in different domains of research. However, for a discipline to develop new customs, the benefits arising from these need to be clear: in the case of reproducibility, it may be difficult to pinpoint specific and measurable advantages at the micro or meso levels (see **section 2**), which can hinder progress in disciplinary communities.

Nevertheless, some disciplines are very advanced in their application of reproducible workflows across the research process and including publication. For example, particle physics is at the forefront of this discourse, and it is interesting to understand the key reasons behind it:

- Infrastructures such as those built by the European Organization for Nuclear Research (commonly referred to as CERN) are very expensive and therefore shared. Data sharing is mandated via organisational policies and checking other people's work is routine

- Experiments require broad collaboration and trust, meaning that transparency with regard to code, data and methods is a key asset

> *"With over 5,000 physicists in an experiment, there are groups that manipulate the data and process it, and then we can just use that. So many people are contributing across different dimensions and sharing their work openly: it's a collaborative effort."*
> *Researcher*

In many other scientific domains, reproducible publication practices are a harder sell: at least to some, they appear to imply a substantial time commitment without any immediate benefits. Although individual champions and numerous communities of practice are making efforts to spearhead cultural change[33,34] reproducible publication practices are yet to take off across the board. For these reasons, policies from publishers and research funding organisations can play a key role in balancing out any bottom-up and localised initiatives and setting strong expectations for stakeholders at all levels.

> *"These initiatives are important in the sense that they drive bottom-up activities and that's very important, but in the end, we need not only bottom-up activities… the role of the bottom-up activities is to trigger top-down activities."*
> *Researcher*

30 Association for Computing Machinery (ACM). (2021). Practices Working Group Blog. **https://bit.ly/3jikljq**
31 The Academy of Medical Sciences. (n.d.) Reproducibility and reliability of biomedical research. **https://bit.ly/2ZO4OB4**
32 National Academies of Sciences, Engineering, and Medicine. (2019). Reproducibility and Replicability in Science. The National Academies Press. **https://doi.org/10.17226/25303**
33 Willis, C., & Stodden, V. (2020). Trust but Verify: How to Leverage Policies, Workflows, and Infrastructure to Ensure Computational Reproducibility in Publication. Harvard Data Science Review, 2(4). **https://doi.org/10.1162/99608f92.25982dcf**
34 Westwood, S. (Twitter). (2021). I'm curious, what got you involved in Open Science/ replication crises? **https://bit.ly/3uH2S8O**

Meso level: International reproducibility networks

As noted above, reproducibility takes different shapes based on disciplines: as a result, not only do requirements vary, but also discussions are not at the same stage of maturity across the board. In a sense, it is unavoidable for these conversations to happen in parallel rather than jointly, but initiatives such as the UK[35] (see also case study on page 25), German[36], Swiss[37], Australian[38], Slovak[39] and Italian[40] Reproducibility Networks have the potential to make a difference. Although most of these networks are relatively young and their impact is difficult to fully assess at this stage, potentially they can:

- Help connect the dots between peer-led discussions (which are relatively young and disconnected, across different disciplines) and other stakeholder groups
- Support collaboration across national boundaries
- Provide an extent of coordination

> *"Some [stakeholder groups] are not working at all, just not interested, others are very progressive, and really trying to pull others along because they see the value of trying to do these things. The ones that are most active are doing it collaboratively, especially those that work across disciplines."*
> *Infrastructure provider*

In this context, we note that national and international thought leadership around reproducibility has been developing over the past few years. For example, project contributors commented on the importance of drawing attention to failed reproduction attempts of studies within a discipline as an approach to raising awareness and kick-starting the reproducibility conversation in areas where this may not be recognised. Overall, it should be noted that it is difficult to assess the impact of activities focusing on reproducibility separately from other related open science practices: for example, reproducibility and (open and/or FAIR) data sharing go hand in hand, and it would be very difficult to discuss one without the other.

Case study: The UK Reproducibility Network

The **UK Reproducibility Network (UKRN) (ukrn.org)** was established in March 2019 to bring together and coordinate efforts to improve research quality across the UK. Its structure includes several distinct but interacting components, namely (i) local networks of researchers; (ii) institutional members; and (iii) external stakeholders such as research funding organisations, publishers, and other sector organisations. UKRN has grown rapidly: at the time of writing, it includes local networks at over 50 UK institutions and 20 institutional members.

A key feature of UKRN's work is the support it provides to existing initiatives, many of which were developed by early career researchers: UKRN works with the founders of these initiatives to amplify and promote them among its members. Other Reproducibility Networks, modelled on UKRN, have recently emerged in other countries, with 11 now established or in the process of being established.

In September 2021, the UKRN was awarded £4.5m from the Research England Development (RED) Fund, "to enable the network to scale up its activities, and accelerate the uptake of open research practices across the sector."[41]

35 UK Reproducibility Network. (n.d.). Welcome to the UK Reproducibility Network. **https://bit.ly/3lW60er**
36 German Reproducibility Network. (n.d.). German Reproducibility Network. **https://bit.ly/3AXeshB**
37 Swiss Reproducibility Network. (n.d.). SWISSRN. **swissrn.org**
38 Australian Reproducibility Network. (n.d.). Welcome to the Australian Reproducibility Network. **https://bit.ly/3DVu6w3**
39 Slovak Reproducibility Network. (2021). Slovak Reproducibility Network. **https://bit.ly/3FXO9f0**
40 Salvato, G. (Twitter). (2021) The Italian Reproducibility Network, a star is about to be born! Stay tuned for more information. **https://bit.ly/2YrePUr**
41 UK Reproducibility Network. (2021). Major funding boost for UK's open research agenda. **https://bit.ly/3uGpcQ0**

Meso level: Institutional expectations for research reproducibility

Our interviews with research performing organisations highlighted that, at present, it is not typical for them to have dedicated policies focusing on research reproducibility. It is, however, increasingly common to mention reproducibility in passing, in the context of other institutional policies or requirements (similarly to research funding organisations, see **page 29**).

> *"In open science we have three different policies. First, we made the data policy, and then we had the publication policy, and then the latest one is an open research policy. It combines the other two but has the whole research process angle to it. For example, in the data policy we have some FAIR principles, and the idea of reproducibility is there."*
> *Research performing organisation*

Research performing organisations tend to make significant investments when funder or policy mandates are introduced: for example, this was the case in the UK when, in 2015, the Engineering and Physical Sciences Research Council introduced new expectations around research data management, which prompted universities to address this area more strategically.[42]

Later in this section, we note that, in most cases, reproducible research practices are not part of funder mandates. As a result of this, it is likely that research performing organisations will continue to monitor the landscape and address research reproducibility via ad-hoc approaches and based on their individual strategies and researcher bases. An example of this is the decision by the Luxembourg Centre for Systems Biomedicine (LCSB) at the University of Luxembourg to partner with SciCrunch[43] to enhance internal quality control, as part of their Responsible and Reproducible Research (R3) initiative.[44]

Meso level: The role of publisher requirements and reproducibility guidelines

Publishers play an important role in the reputation economy that underpins a large portion of academia. In particular, they act as a critical choke point before authors are able to share journal articles – a highly valued currency: as publishers and, more specifically, journals hold the keys to a researcher's success (at least in part), they are also in a strong position to make demands and, importantly, provide support.

Checklists or guidelines for editors, peer reviewers and authors are "simple yet powerful tools"[45] that journals can use to encourage reproducible publication practices. These would give all those involved a tool to ensure that, as a minimum, a given set of research objects is available alongside a research article, either at the time of submission or at the time of acceptance. The main difficulty is to identify what such a set of research objects would look like, and this largely depends on disciplines. In addition, checklists and guidelines may or may not be strictly enforced, depending on disciplinary customs and journal choices – for example, a limited number of journals considers irreproducibility as a fair cause for article rejection. In practice, this could take the form of a 'revise and resubmit' editorial decision, following a failed reproduction by the journal, data editor, peer reviewer(s) or third-party verification agencies.[46,47]

> *"I'm actually against publisher-specific bespoke checklists or reporting guidelines, because it would be much easier if there were community driven standards that all publishers could adopt."*
> *Publisher*

42 Jisc. (2018). Meeting the requirements of the EPSRC research data policy. **https://bit.ly/3lasuIc**
43 Research Information. (2020). SciCrunch announces Luxembourg collaboration. **https://bit.ly/3Dir8Bz**
44 Univeristié Du Luxembourg. (n.d). Responsible and Reproducible Research (R3) **https://bit.ly/3uHDL5Y**
45 Goeva, A., Stoudt, S., & Trisovic, A. (2020). Toward Reproducible and Extensible Research: from Values to Action. Harvard Data Science Review, 2(4). **https://doi.org/10.1162/99608f92.1cc3d72a**

Case study: Policy and protocol on third-party verifications at the American Economic Association (AEA)

The AEA is a non-profit scholarly association dedicated to the discussion and publication of economics research. Their journals have a strict **Data and Code Availability Policy (https://bit.ly/3aV3DCd)** noting their willingness to "publish papers only if the data and code used in the analysis are clearly and precisely documented and access to the data and code is non-exclusive to the authors". The AEA also has an in-house **Data Editor**[48], whose mission is to "design and oversee the AEA journals' strategy for archiving and curating research data and promoting reproducible research".

For the most part, the AEA conducts reproducibility checks in-house, but can also rely on **third-party replicators (https://bit.ly/3G5hNz6)** when, for a variety of reasons, checks cannot be delivered in a timely fashion. The AEA provides clear **guidance (https://bit.ly/3l8oisy)** for both in-house and third-party replicators, including the following steps:

- Download the author's 'replication archive'
- Follow a checklist to conduct a reproducibility check
- Write a report based on the findings of the above check (see an **example (https://bit.ly/3l8opEu)**)
- Send the report to the Data Editor

Replicators are required to make a clear and evidence-based assessment of an article's reproducibility, which may range from 'full reproduction' to 'not able to reproduce most or all of the results': this informs the decisions of AEA Data Editor, who may require the author(s) to make changes and resubmit their work until the 'replication archive' is accepted.

Notably, an acceptance report arising from the above reproducibility check **is required (https://bit.ly/3Db66oe)** to start the copy-editing process that eventually leads to publication.

Note: the language used by the AEA tends to mix 'replication' and 'reproducibility', but, in practice, their ***guidance (https://bit.ly/3BcN1Sb)*** *uses the definition of 'reproducibility' followed in the present report.*

46 Office of the AEA Data Editor. (2021). Guidance on testing replicability of code. https://bit.ly/3Afzvf0
47 GitHub (n.d.). ReScience C: Frequently Asked Questions. https://bit.ly/2Z8U6Fb
48 Vilhuber, L. (2021). Report by the AEA Data Editor. AEA Papers and Proceedings, 111: 808-17. https://doi.org/10.1257/pandp.111.808

Checklists and guidelines also have an educational value and can play a role in raising awareness about research practices whenever they are implemented and shared with prospective authors and other stakeholders in the publication process.

Although it is difficult to gauge the impact of checklists and guidelines at the system level, we note that some initiatives are making great strides in the right direction:

- The TOP Guidelines provide research funding organisations, publishers, and research performing organisations with customisable options to develop new norms in line with their goals, and have been implemented by over 1,100 Journals[49,50,51]
- The EQUATOR network contains a comprehensive searchable database of 470 reporting guidelines in the field of health research[52]
- The ARRIVE guidelines are a checklist of information to include in publications describing animal research, to enable readers and reviewers to scrutinise the research adequately, evaluate its methodological rigour, and reproduce the methods or findings[53]

Individual journals are also known for driving change with regard to reproducibility, and we highlight, for example:

- The reproducibility requirements of the American Economic Association[54]
- The availability of a "Reproducible Results Section" in the Journal of Water Resources Planning and Management (part of the American Society of Civil Engineers (ASCE))[55]
- The introduction of a new article type called "Verification Reports" in the journal Cortex, seeking to evaluate the claims in published research through reanalysis of the original study data[56,57]
- The guidance on reproducibility and Jupyter Notebooks developed for authors publishing in American Geophysical Union journals[58]
- The Image Processing On Line (IPOL) journal, where each article contains a text on an algorithm and its peer-reviewed source code, with an online controlled demonstration[59]
- The ReScience journal ran a "Ten Years Reproducibility Challenge" to encourage authors to check the results produced by code developed in the past, including if this can run on current hardware/software and whether it still returns the exact same results[60]

49 Center for Open Science. (n.d). Top Guidelines. **https://bit.ly/3m1Ckwt**
50 Center for Open Science. (n.d.). Sample Implementation of Guidelines for Transparency and Openness Promotion (TOP). Journal Policies and Practices. **https://bit.ly/3ngGOi6**
51 Yeston, J,S. (2021). Progress in data and code deposition. **https://bit.ly/3ldpKtO**
52 EQUATOR Network. (n.d.). Enhancing the QUAlity and Transparency Of health Research **https://bit.ly/3G7Y4i3**
53 National Centre for the Replacement, Refinement & Reduction of Animals in Research. (n.d.). ARRIVE Guidelines.. **https://bit.ly/3Gb1sJo**
54 American Economic Association. (n.d). Policy and Protocol on Third-Party Verifications. **https://bit.ly/3vufL6N**
55 Rosenberg, D. E., Jones, A. S., Filion, Y., Teasley, R., Sandoval-Solis, S., Stagge, J. H., Abdallah, A., Castronova, A., Ostfeld, A., & Watkins, D., Jr. (2021). Reproducible Results Policy. Journal of Water Resources Planning and Management, 147(2). **https://doi.org/10.1061/(asce)wr.1943-5452.0001368**
56 Chambers, C. D. (2020). Verification Reports: A new article type at Cortex. Cortex, 129, A1–A3. **https://doi.org/10.1016/j.cortex.2020.04.020**
57 Elsevier. (n.d). Verification Reports – Guide for Authors. **https://bit.ly/3AWAbpX**
58 Advancing Earth and Space Science. (n.d.). Data and Software for Authors **https://bit.ly/3ldHVQ2**
59 Image Processing On Line (IPOL). (n.d.). Image Processing On Line. **https://bit.ly/3aW9pDw**
60 ReScience C. (n.d.). Ten Years Reproducibility Challenge. **https://bit.ly/3ndY1c1**

- The development of Executable Research Articles (ERA) by eLife and Stencila, which allows authors to publish computationally reproducible research articles that use optimised Docker images (see **section 5**)[61,62]

Macro level: The role of research funding organisations in setting reproducibility policies

Many interviewees see funder requirements as the core tool to push research reproducibility forward: research funding organisations hold significant power and, in most cases, researchers cannot operate without their support. The best-known example of funder initiatives in this domain is the Dutch Research Council's (also known as NWO) 'Replication Studies' programme[63,64] (see case study on **page 30**), which ran from 2016-2019 and offered funds for both replication and reproduction studies; however, the programme cannot be classified as a policy mandate.

Within research funding organisations, the topic of reproducibility is currently nested under broader policies and positions, and it is not always explicitly mentioned. For example, policies focusing on other aspects of open scholarship (e.g. open data) might refer to reproducibility. Indeed, project contributors noted that reproducibility requirements should be integrated in other neighbouring policies, as reproducible publication falls within the broad umbrella of open science and open research practices. Other related policies, such as research integrity policies, may also mention research reproducibility along with rigour and transparency.

> *"We have 'good research practice' guides here, so we try to incorporate almost everything into those. That includes open access, data management, anything at all that we want people to do. That saves us having lots of different sets of policies, which we have had in the past."*
> *Research performing organisation*

Our interviewees in the research funding community did not perceive a need for immediate action at the macro-level when it comes to research reproducibility. They noted that part of this is due to the difficulty in setting requirements for grantees across different disciplines, but many also recognised that the overarching goal is open science, with reproducibility being one of various concerns. For example, it is still unclear who should fund data curation and sharing efforts[65]. This is a necessary (but not sufficient) requirement for reproducible publication and is yet to be fully resolved by higher education and research players.

Macro level: The growing interest from government-level players

To date, policymakers have not been significantly involved in the research reproducibility discourse. However, their interest in this area is growing as part of overarching commitments to open science practices.

For example, the Second National Plan for Open Science developed in France extends the scope of the country's previous commitments around open science and "is firmly attached to a European-wide vision" of open science[66]. The Plan includes mentions of reproducible publication practices particularly with regard to opening up and promoting source code and recognises that this is an important requirement to ensure reproducibility and enable knowledge sharing.

61 eLife. (2021). eLife and Stencila announce roadmap for bringing reproducible publishing to more authors. https://bit.ly/3ivFdDK
62 Stencila. (n.d.). Executable document pipelines. https://bit.ly/3CeiV0M
63 Dutch Research Council (NWO). (n.d.). Replication Studies. https://bit.ly/3BgytRe
64 Dutch Research Council (NWO). (2020). Replication Studies third round: repetition of important research. https://bit.ly/3msMXHA
65 Digital Science, Hahnel, M., Borrelli, L. M., Hyndman, A., Baynes, G., Merce Crosas, Nosek, B., Shearer, K., Selm, M. V., Goodey, G., & Nature Research. (2020). The State of Open Data 2020. https://doi.org/10.6084/M9.FIGSHARE.13227875.V2
66 Ouvrir la Science. (n.d.). Second National Plan for Open Science. https://bit.ly/3lbskAf

Case study: NWO's Replication Studies programme

Dutch funder NWO has been funding so-called **"Replication Studies" (https://bit.ly/3FmYJw2)**, including "reproduction - replication with existing data" and "replication with new data." Between 2016 and 2019 NWO ran a pilot programme with a total budget of €3m to be distributed via three calls for proposals. The programme was started to **focus on repeating "cornerstone" research (https://bit.ly/3a9ahEE)**, i.e. published works that had a significant impact on science, policy or public debate. In the last round, NWO's Replications Studies programme only funded the repetition of research (i.e. replication), although reproduction-focused studies were still eligible. The programme is now under evaluation after its last funding round.

NWO's strategic aims were to "gain experience that can lead to insights into how replication research can be effectively included in research programmes" and "lead to insights into and a reflection on the requirements that NWO sets for research in terms of methodology and transparency". This shows the importance of gathering evidence and requirements from the research community and carefully considering how these can be implemented in the context of funder policies.

Our interview with NWO highlighted that this type of funding mechanism can be important to raise awareness, particularly in the short-to-medium term and while practices continue to evolve across different disciplines. However, ad-hoc funding for reproducibility and replication is expected to become superfluous in the long run, as these activities become more common and can be supported as part of research grants.

The UK Research and Development Roadmap covers reproducible publication practices and takes a very similar position, making a commitment to mandate open publication and incentivise open data sharing, "so that reproducibility is enabled, and knowledge is shared and spread collaboratively"[67]. It is also worth noting that the Science and Technology Committee of the UK Parliament has recently launched an inquiry into reproducibility and research integrity to further investigate these issues and assess the potential role of UK Research and Innovation.[68] In both examples above, it is evident that policymakers can affect how the research enterprise develops reproducibility-related practices. Given their distance from day-to-day research, policymakers focus primarily on setting high-level expectations and supporting their implementation via strategic funding to research performing organisations, research programmes and key digital infrastructures.

Micro, meso and macro-level contributions in the context of policy development

The policy discourse around research reproducibility, including at the publication stage, is currently developing. The 'policy cycle' is a helpful tool to further understand the steps needed to take the discussion forward. It can be split into two main portions, one working across disciplines and the other within disciplines (see **Figure 3**)[69]:

- The cycle across disciplines takes place at the meso and macro levels and runs from the definition of a problem towards the development of a policy to address it and its subsequent implementation, enforcement and evaluation

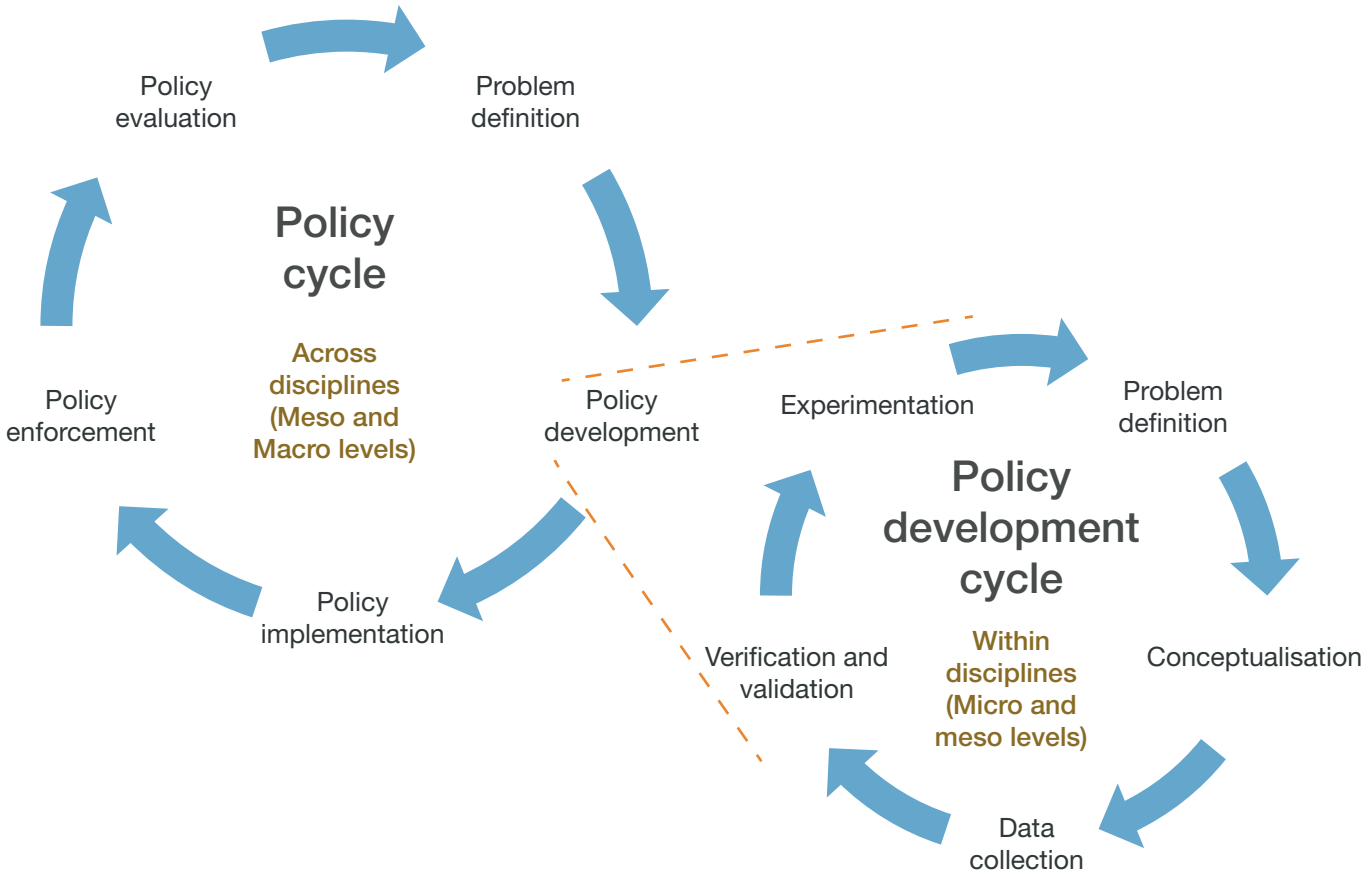
- On the other hand, the conversation within disciplines happens at the micro and meso levels, and includes the conceptualisation of possible policy solutions, data collection, verification/validation and experimentation, until a suitable policy position is reached

67 Department for Business, Energy & Industrial Strategy. (2021). UK Research and Development Roadmap (Policy Paper).**https://bit.ly/3ula1G6**

68 UK Parliament. (n.d.). Reproducibility and research integrity. **https://bit.ly/3ulaaJE**

69 Janssen, M., & Helbig, N. (2018). Innovating and changing the policy-cycle: Policy-makers be prepared! Government Information Quarterly, 35(4), S99–S105. **https://doi.org/10.1016/j.giq.2015.11.009**

Figure 3. A policy cycle interpretation of the research reproducibility discourse

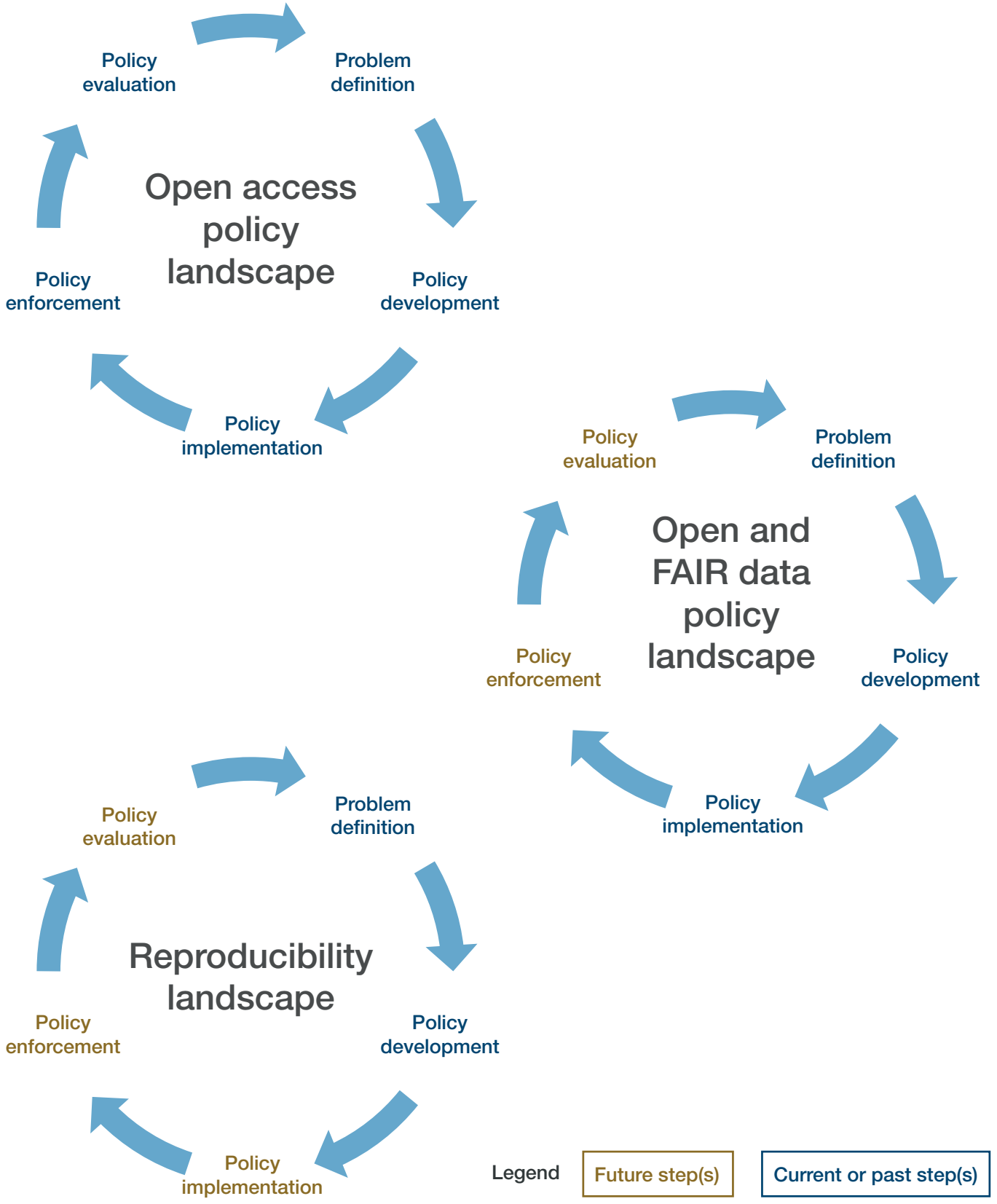


We argue that the 'problem definition' stage in the policy cycle has taken place across the board, but very few disciplines have managed to rise through the 'policy development' stage. Our discussion above emphasises the significant role that disciplinary customs can play in driving reproducible publication practices, and the policy cycle shows that players at the micro level have a role to play in policy development. Today, this is happening slowly and, often, in silos, which hinders progress at the meso and macro levels (with some notable exceptions, as discussed above). As a result, the discourse around reproducibility is somewhat stuck in the policy cycle.

> *"There are efforts, like the UK Reproducibility Network for example, to bring together several initiatives, aiming to harmonise or coalesce ideas. But I think for the moment [the landscape] is a bit haphazard."*
>
> *Learned society*

To provide further clarity, it is helpful to draw a comparison with the open access and open data policy landscapes (see **Figure 4**). With regard to open access, all steps in the policy cycle have happened to date and, arguably, multiple cycles/iterations of open access policies have taken place. A large extent of experimentation can be observed around open access policies and business models, partly because significant amounts of funding are involved. On the other hand, in the case of open and FAIR data, the discussion is less developed: policies have been introduced in some disciplines and by some funders, but these are rarely enforced. Although the above are oversimplifications that do not take into account national, disciplinary and other variations, it is not surprising that the reproducibility discourse is less developed than these comparators – not least because it largely relies on a culture of open science that is not yet fully developed.

Figure 4. Comparison between open science policy landscapes



4. Incentivising and supporting reproducible publication practices

Reproducibility efforts are not currently incentivised within the research process, and reproducible publication practices are commonly perceived as additional, unrewarded activities. To reduce the pressures arising from ever-growing expectations on researchers, research performing organisations can establish staff positions to support reproducibility and facilitate training and capacity building in this area.

Incentives for reproducible publication

In an ideal world, "reproducibility labour would be baked into the research process, so that the effort it takes is indistinguishable from the research effort itself".[70] This is not the case in today's research enterprise, and research practices that are conducive to reproducible publication are perceived by researchers as extra work to be added on top of a regular project. Based on our discussion so far, it is clear that reproducibility cannot be seen as a "bolt-on" feature added at the time of publication, as it comprises a set of practices that permeate the whole research process: for reproducibility to take a more prominent position, an extent of cultural change is needed.

> *"And once [reproducibility] becomes possible, once it becomes easy, once it becomes normative then there's kind of no reason not to do it. And it certainly should in principle improve the quality of our research outputs, improve the efficiency with which we generate knowledge that can benefit society."*
> *Researcher*

In the long term, the best outcome would be to shift from a tokenistic appreciation of reproducibility efforts (e.g. promotions, salary increases, badges, citations) towards a broader recognition that research should be reproducible by default. However, our interviewees reported that current incentives around reproducible publication are limited and not particularly effective, unless they come in the form of a requirement imposed by one's journal of choice (which is, however, extrinsic leverage rather than intrinsic motivation).

It is therefore essential to identify new ways to encourage and reward behaviours conducive to reproducibility, and two main suggestions have been advanced by our interviewees:

- Making reproducibility workflows and checks as easy as possible for researchers, minimising barriers to entry, to ensure that any new expectations are met with the minimum additional effort
- Reprioritising open science practices in recruitment and promotion committees and grant funding (including, but not limited to, reproducibility), to consider these alongside traditional or other metrics

70 Association for Computing Machinery. (n.d.). Reproducibility PRINCIPLES: Taking the pulse. https://bit.ly/3ow2w45

> *"I believe it comes down to hiring practices and funding practices, and there are a number of activities underway to try and get data and code and other outputs recognised in the system for research assessment."*
> *Publisher*

Several players in the open research landscape are already working in these directions, including for example:

- The San Francisco Declaration on Research Assessment (DORA)[71] and the Leiden Manifesto for Research Metrics[72] have been working to promote more balanced practices in research(er) assessment (for example, DORA is actively promoted by UK funding organisations Wellcome and UKRI[73, 74] and has been signed by other funders such as DFG in Germany)[75]
- The European Research Council, which has recently banned mentions of the journal impact factor from their bids[76]
- Utrecht University, which has decided to exclude the impact factor in hiring and promotion decisions[77]

Regardless, at the time of writing the 'publish or perish' paradigm is still very much alive and this significantly affects researchers' decisions when it comes to setting priorities in their everyday practices and workflows.

In addition, the research process and the set of expectations of researchers are growing in complexity across many disciplines, which leaves limited room to implement the range of activities required for reproducible research: to accommodate new practices, pressures on researchers will need to be carefully managed, for example by slowing down research projects or by providing support to researchers.

> *"For scientists, this is really a great frustration. They are asked to do ten thousand different jobs. Although people do explain to researchers how to do these jobs, people never think that they have already got too much work on their hands. And it just doesn't add up."*
> *Publisher*

Relieving time pressures to pursue reproducible publication practices

Although our definition of reproducibility is relatively straightforward, the skill sets required to re-run someone else's code or assess the quality of a dataset are far from widespread. For example, a researcher (either on their own or in the capacity of a peer reviewer) may be a leading expert in their area, but at the same time may not have the skills to carry out a reproducibility check.

> *"We need to make sure that the people can look at a reproducible manuscript and pull something out of it. I doubt that most people would be so versatile that you could throw any analysis at them, and they'd know what's going on. They might not even code in that language."*
> *Researcher*

The support of research performing organisations can be instrumental in relieving some of the time pressures on individual researchers and complement their skills where lacking. Research performing organisations are in a unique position to assist their staff via new support

71 Declaration on Research Assessment (DORA). (n.d.). Sign DORA. **https://sfdora.org**
72 Hicks, D., Wouters, P., Waltman, L., de Rijcke, S., & Rafols, I. (2015). Bibliometrics: The Leiden Manifesto for research metrics. Nature, 520(7548), 429–431. **https://doi.org/10.1038/520429a**
73 Wellcome. (n.d.). Guidance for research organisations on how to implement responsible and fair approaches for research assessment. **https://bit.ly/3a9A53s**
74 UKRI. (n.d.). Research integrity. **https://bit.ly/3Ab2YXG**
75 DORA (Twitter). (2021) The German Research Foundation (@dfg_public) has signed DORA. **https://bit.ly/3mwRDwm**
76 Matthews, D. (2021). European Research Council bans journal impact factor from bids. Times Higher Education. **https://bit.ly/2YkaGlu**
77 Woolston, C. (2021). Impact factor abandoned by Dutch university in hiring and promotion decisions. Nature, 595(7867), 462–462. **https://doi.org/10.1038/d41586-021-01759-5**

staff such as data stewards, data curators, research software engineers or subject librarians, as these can provide advice and practical support as research projects develop[78, 79, 80] and we note that the specific locus of support tends to vary by institution.

Our interviews pointed out that efforts to support reproducible publication practices are often difficult to fund (see **section 6**), as they require a strategic commitment to open research practices and a broader appreciation of the importance of data curation and other practices. Things are, however, changing in several research performing organisations[81, 82, 83] even if the process of cultural change in this direction has been slow.

Case study: New York University's (NYU) approach to supporting researchers with research reproducibility

NYU provides a wide range of **data management services (https://bit.ly/3lZ1Imq)**, like many universities worldwide. What makes their approach unique, however, is the appointment of a dedicated Research Data Management and Reproducibility Librarian – a position that few (if any) other universities have.

The NYU RDM and Reproducibility Librarian is a post currently held by Vicky Rampin - the only person to hold this position at NYU, and the first librarian in the world to have reproducibility formally in their job title and job description. In this unique post, the RDM and Reproducibility Librarian is responsible for several areas: consultations (e.g. one-to-one or group sessions to solve specific issues), instruction (e.g. workshops, embedded/by-request sessions for specific classes, departments, and programs), outreach (e.g. events, social media, outreach to patrons), infrastructure building (e.g. supporting the university in developing fit-for-purpose service provision) and research (e.g. direct investigation of topics such as reproducibility, software preservation, research workflows). The Research Data Management and Reproducibility Librarian works in close collaboration with the RDM Librarian, building on an understanding that there is significant overlap between these two areas.
The data management guidance provided by NYU also covers specific software solutions that enable reproducible publication practices, such as the **Open Science Framework (https://bit.ly/3oY8DOy)**, **Jupyter notebooks (https://bit.ly/3FE47uS)**, **GitHub and GitLab (https://bit.ly/3ApOeEt)** and **ReproZip (https://bit.ly/2Z8hh2P)** (see **section 5** for more information on these). This type of guidance is currently uncommon at research performing organisations and communicates a strong commitment to research reproducibility to the local academic community.

78 Kurapati, S. (2019). Becoming a Data Steward. LSE Impact Blog. **https://bit.ly/2ZYFZmd**
79 Teperek, M., & Plomp, E. (2019). The role and value of data stewards in Universities: a TU Delft case study on data stewardship. **https://doi.org/10.5281/ZENODO.2684278**
80 Imperial College London. (n.d.). Subject Support. **https://bit.ly/2WHOdhc**
81 Plomp, E., Andrews, H., Love, J., den Heijer, K., Dintzner, N., Ilamparuthi, S., Wang, Y., & Turkyilmaz-van der Velden, Y. (2021). Communicating Open Science at TU Delft. Open Working. **https://bit.ly/2WMk9Bc**
82 Rice, R. (2021). Welcome to Research Data Stewards A New Role. The University of Edinburgh. **https://bit.ly/3AhPAkh**
83 Maastricht University. (n.d.). Data stewardship services. **https://bit.ly/3Acv1WD**

Developing new support and training pathways

A report by the Research Data Alliance[84] further expands on the potential role of research performing organisations and notes that more training on reproducibility would be desirable. At the same time, our interviews highlighted the dangers of monolithic and overly standardised approach to supporting reproducible publications practices, which shows the importance of acknowledging diversity when developing new mechanisms in this area.

A range of support and training pathways, both within and beyond research performing organisations, are currently blossoming worldwide, and we present a selection of examples in **Table 3**. However, it should be noted that these examples are the exception rather than the rule, and several contributors highlighted that more structured support for reproducible publication practices would be welcome.

> *"In Medicine, for instance, they are quite invested in the promotion of open science, reproducibility and replicability, but they tend to do so quite monolithically, assuming that they only host one epistemic culture."*
> *Researcher*

Table 3. Examples of support pathways

Support pathway	URL	Focus
Best Practices for Writing Reproducible Code	**https://bit.ly/3aZEM01**	Courses and workshops
Digital Competence Centre	**https://bit.ly/3Ab3eWp**	Institutional training provision
Increasing Openness and Reproducibility in Research	**https://bit.ly/3IfX9Ux**	Institutional training provision
Openness and Reproducibility Research Practices Training	**https://bit.ly/3C64JqW**	Commercial training provision
Reproducibility for Everyone[85]	**https://bit.ly/3G6ofG6**	Peer- or community-led guides/workshops
ReproducibiliTea	**https://bit.ly/2XwCYZo**	Community meetings or exercises
Reproducibility Hub	**https://bit.ly/3iB1YpL**	Institutional training provision
ReproHacks	**https://bit.ly/3acWjBK**	Community meetings or exercises
Rigor and Reproducibility Planning	**https://bit.ly/2Ynbllu**	Institutional training provision
Training For Reproducibility Verification	**https://bit.ly/3iCU13d**	Peer- or community-led guides/workshops
Turing Way Handbook	**https://bit.ly/3iA7fhc**	Peer- or community-led guides/workshops

84 Peer, L., Arguillas, F., Honeyman, T., Miljković, N., Gehlen, K. & CURE-FAIR WG Subgroup 3. (2021). Challenges of Curating for Reproducible and FAIR Research Output. Research Data Alliance. **https://doi.org/10.15497/RDA00063**

85 Auer, S., Haeltermann, N. A., Weissberger, T. L., Erlich, J. C., Susilaradeya, D., Julkowska, M., Gazda, M. A., Schwessinger, B., Jadavji, N. M., Abitua, A., Niraulu, A., Shah, A., Clyburne-Sherinb, A., Guiquel, B., Alicea, B., LaManna, C., Ganguly, D., Perkins, E. & Jambor, H. (2021). A community-led initiative for training in reproducible research. eLife. **https://doi.org/10.7554/elife.64719**

Our interviews also touched on the potential role of reproducibility champions from the academic community, as these can provide awareness-raising, training and cultural change support in specific areas relevant to their disciplinary expertise.[86]

More broadly, training on reproducible publication practices for university students could be improved, too, including as part of existing modules. In some disciplines, reproducibility skills are already being taught very early on: for example, in high energy physics and some branches of economics and the life sciences, it is not uncommon to work with real datasets and code at the BSc/MSc level. However, across the board, training on reproducibility is not an established part of student curricula.

> *"To my recollection we've had one mandatory course which was in research integrity, including plagiarism and cheating… We only have mandatory courses when it's related to legal challenges… For this more normative issue, that's not going to happen."*
> *Researcher*

86 Silver, A. (2017). Collaborative Software Development Made Easy. Nature. 550, 143-144. https://doi.org/10.1038/550143a

5. Technological innovation

A mix of established and innovative technical solutions to enable reproducible publication practices are available across the research landscape, including not-for-profit and commercial providers. Many stakeholders are aware of the tools and services available, but uptake varies by discipline and often depends on the balance of qualitative and quantitative research in one's work.

Digital infrastructures

In this section, we discuss a range of technological solutions available in today's research landscape that can have an impact on reproducible publication practices. Our interviews highlighted a shared view that many of the tools needed to work and, particularly, publish in a reproducible way are already available. Interviewees do not feel that anything in particular is currently missing in the reproducibility landscape, but note that varying levels of technical expertise across users and a lack of connectivity (between tools themselves, but also between tools and research workflows) are hindering efforts.

> *"There's lots of innovation needed in the infrastructure landscape. It's not about inventing something new that doesn't exist, it's about making the things that do exist better… and to lower the barrier to entry for people at different stages of knowledge."*
> *Infrastructure provider*

Given how many different (sub)disciplines exist, the consensus is that it is not desirable to constrain the range of tools used by researchers. This also means accepting that commercial tools have a role to play in serving the research community; however, our interviews indicated that the balance between commercial and publicly funded infrastructures should be monitored in line with the Principles of Open Scholarly Infrastructure,[87] to avoid vendor lock-in and other barriers such as lower access to expensive tools in countries where research budgets are limited.

> *"We want to prevent vendor lock in and one way to do that is to build open standards so that there's always a competition, there's always third parties that can come in and build a better service with that minimal standard."*
> *Researcher*

Awareness and uptake of reproducibility-focused tools and services vary by discipline, and the maturity of practices within a discipline is affected by (i) the balance of qualitative versus quantitative research; (ii) the extent to which computational approaches are used; and (iii) the extent to which a discipline works with digital vs physical "data". In particular, researchers who write code as part of their work tend to more quickly recognise the research objects that could make their published findings reproducible, as these are already part of their everyday practices (although in many cases not sufficiently curated to enable reproducibility): it is therefore not surprising that

87 Openly Scholarly Infrastructure. (2020). The Principles of Open Scholarly Infrastructure. **https://bit.ly/3pliPB9**
88 Obels, P., Lakens, D., Coles, N. A., Gottfried, J., & Green, S. A. (2020). Analysis of Open Data and Computational Reproducibility in Registered Reports in Psychology. Advances in Methods and Practices in Psychological Science, 3(2), 229–237. **https://doi.org/10.1177/2515245920918872**

many of the tools and services we identified in this study cater to computational reproducibility.[88] Our conversations often covered the use of tools such as Docker, Jupyter Notebooks, Binder and, more broadly, reproducible environments (see Table 4 for more information on these tools). Beyond computational reproducibility, we also note the growing importance of badging and certification agents, such as cascad (particularly focusing on economics), which may play a growing role in the future.

Table 4. Examples of support pathways

Tool or service	URL	Focus
cascad	https://bit.ly/3B0gtKc	Reproducibility checking
CODECHECK[89]	https://bit.ly/3nwsAtR	Independent execution of computations underlying research articles
Docker	https://dockr.ly/3aW723R	Software containerisation
eLife ERA	https://bit.ly/3oGCWcz	Executable research articles
ISA Framework	https://bit.ly/3pkCqRW	Whole research process (Life sciences)
Jupyter Notebooks	https://bit.ly/2Z8Ay4b	Code sharing and documentation
Binder	https://bit.ly/2Yw4SoX	Interactive and reproducible environments
Code Ocean	https://bit.ly/3vAU3hA	Computational research platform
Gigantum	https://bit.ly/3GiRyFF	Computational research platform
LabArchives	https://bit.ly/3G7jlse	Electronic Lab Notebook
LabFolder	https://bit.ly/3jolLsW	Electronic Lab Notebook
Octopus (in development)	https://bit.ly/3C6nESu	Whole research process (Sharing and documentation of research objects as research is developed)
Observable[90]	https://bit.ly/3ixJypO	Computational research platform
ReproZip	https://bit.ly/3piFrSO	Reproducibility packaging/bundling solution (research compendia)
Whole Tale	https://bit.ly/3m2Ftfs	Reproducibility packaging/bundling solution (research compendia)
R Markdown and R Notebooks	https://bit.ly/2Z7J6rF https://bit.ly/3BdU8Jj	Code sharing and documentation
R-Squared	https://bit.ly/2YqDojW	Reproducibility checking
Renku (See also case study on page 41)	https://bit.ly/3DWuf24	Whole research process (Collaborative Data Science)
Stencila	https://bit.ly/3m3lnS8	Executable research articles and Executable document pipelines

89 Nüst, D. & Eglen S, J. (2021). CODECHECK: an Open Science initiative for the independent execution of computations underlying research articles during peer review to improve reproducibility [version 2; peer review: 2 approved]. F1000Research, 10(253). https://doi.org/10.12688/f1000research.51738.2

90 Perkel, J. M. (2021). Reactive, reproducible, collaborative: computational notebooks evolve. Nature, 593(7857), 156–157. https://doi.org/10.1038/d41586-021-01174-w

Table 4 is limited in scope and excludes online repositories (e.g. **Zenodo (https://bit.ly/3nfdLLR)**, **figshare (https://bit.ly/30HxRqt)**, **OSF (https://bit.ly/3C4IFg7)** (see also case study on page 41), **re3data (https://bit.ly/3vzJX0s)**, **Dryad (https://bit.ly/3G7NQ1n)**, **CERN Open Data portal (https://bit.ly/2XwkF6A)**), source code repository hosting services (e.g. **GitHub (https://bit.ly/3DYDn6z)**, **Bitbucket (https://bit.ly/3jpGFYJ)**), other software to implement reproducible analytical pipelines (e.g. **Travis CI (https://bit.ly/3AWSzzf)**) and overarching general-purpose infrastructures that many online tools and services rely on (e.g. **Amazon Web Services (https://go.aws/3DYDzmj)**, **Microsoft Azure (https://bit.ly/3vx79fy)**, **Google Cloud (https://bit.ly/3pp2JGI)**): these are important to support reproducible publication practices but have different strategic objectives and drivers. Repositories are particularly important because they can serve a large number of use cases where data sharing requirements to enable reproducible publication are simple – for example, cases in which sharing a table or set of media files (e.g. images, audio, video) may be enough, and the main concern is ensuring that these are hosted on a platform with a digital curation strategy.

> *"Because I've had so much use of freely available resources online, I also want to promote as much open research in my own work as possible, because I see the benefits in that are huge."*
> *Researcher*

We recognise that physical as well as digital repositories have a role to play in enabling the reproducibility of research. However, we do not cover physical repositories separately in our discussion: this is because our stakeholder engagement activities and literature review have not identified the publication of reproducible research outputs as a widespread priority in disciplines that are based on non-digital research items.

The innovation gap: service connectivity

Although a wide range of tools and services to enable reproducible publication practices are available, many contributors commented on the issue of service connectivity and interoperability. In short, this refers to the fact that researchers carry out their work by leveraging a vast array of technological solutions and software, but these can rarely 'talk' to each other.

This is the setting where innovation is most needed and, in some cases, infrastructure providers are coming to the rescue by providing ways to connect research objects either throughout the research process or post-hoc. In a simple (and very common) scenario where connectivity issues arise from the need to gather outputs from different sources, OSF Projects[91] or Zenodo Communities[92] may be of help, with the former solution having a focus on keeping all relevant project information in a single page.

91 Bowman, S. (2020). Create a Project. OSF. **https://bit.ly/3uIRGsq**
92 Zenodo. (n.d.). Communities. **https://bit.ly/3vxaV8M**

Case study: Approaches to enhance the connectivity of digital objects

While some of the technical infrastructures described in this section can be considered as standalone tools, others focus on enabling and enhancing connectivity between digital objects and technical solutions. A key feature of these solutions is integration with external services and tools such as **data repositories and source code repository hosting services (https://bit.ly/3Fkegwl)**, **Jupyter notebooks (https://bit.ly/3Bk9vQY)**, **protocols.io (https://bit.ly/3uMPW1x)**, **docker (https://bit.ly/3FkhGPR)** and reference managers such as **Zotero (https://bit.ly/302EHqn)** and **Mendeley (https://bit.ly/3oD0UFK)**. This enables them to (i) minimise friction for collaborators or prospective reusers; and (ii) enhance trust in the research process by enabling transparency.

Example 1: The Open Science Framework
The Open Science Framework (OSF) (cos.io/products/osf) achieves the above by the means of Projects. These allow users to gather research objects from different sources (or **upload them directly to the OSF (https://bit.ly/3lf3eAz)**) and include different sections, e.g. a Wiki, a log of recent activities, registrations and analytics. By default, OSF projects use persistent URLs, but the platform also offers the generation of **digital object identifiers (DOIs) (https://bit.ly/3DdKWWA)**. A sample project created by the OSF team can be viewed **here (https://bit.ly/3neegWr)**.

Example 2: Renku
Renku is centred around computational reproducibility and is a self-hosted open source platform connecting an online git repository with an environment for recording and executing workflows and interactive notebooks (Jupyterhub); it enhances connectivity between digital objects by focusing on the computational steps in the **scientific process (https://bit.ly/2YpHGIn)**. The platform seeks to capture, record and utilise the lineage of results generated through a project and creates a **knowledge graph (https://bit.ly/3iBZ6bY)** based on which individual steps or entire pipelines can be repeated, searched and reused.

Both the OSF and Renku are open source and have a strong focus on collaboration and research sharing and discovery. Importantly, these solutions allow the creation of private or controlled access projects (or even **subsets of projects (https://bit.ly/3psGFLd)**, in the case of OSF), which means that they are likely to be suitable for the analysis and processing of sensitive or otherwise confidential information.

In computationally intensive disciplines, it is important not only to share data and code, but also to "capture the lineage"[93] of one's work. This includes version control, computational environments and, potentially, different programming languages within the context of the same study. Sharing all this information in such a way that reproducibility checks are possible is a bigger challenge and requires more specific approaches, using emerging tools such as Renku.

> *"It's complete chaos, the technology. It's really disastrously disorganised and disastrously decentralised and improperly formatted… The only thing I'm interested in is to be able to find the stuff I need quickly, in one place, without having to jump from one thing or another or to register at thirty different places. So, this is a huge problem."*
> *Publisher*

Finally, connectivity issues are also addressed by research compendia, which serve computational researchers and provide "a standard and easily recognisable way for organising the digital materials of a project to enable others to inspect, reproduce, and extend the research"[94]. In essence, research compendia are structured folders including all the materials, code and documentation required to reproduce and reuse someone else's work; examples can be found on Zenodo[95] or GitHub[96].

Assessing and comparing technical solutions

Given the dependency of reproducible publication practices on disciplinary considerations, it is difficult to develop blanket criteria to assess and compare the usefulness and comprehensiveness of different technical infrastructures. The Gigantum team has made efforts to develop a high-level framework to achieve the above, focusing in particular on computational reproducibility. Their approach to evaluating reproducibility solutions included four key dimensions:[97]

- The individual or group who created the research objects to be reproduced, including any relevant code and research data (the 'Producer')
- The set of research objects needed to reproduce the results and the methods/procedures to achieve this (the 'Project')
- The hardware, data storage and other digital infrastructure needed to reproduce the result (the 'Infrastructure')
- The individual or group who will attempt to run the reproducibility check (the 'Consumer)'

Based on the above, it is then possible to ask some questions to assess and compare solutions, for example:

- How easy is it for the Producer to create a reproducible Project?
- How easy is it for the Consumer to reproduce the Project?
- How flexible is the Infrastructure in terms of location, configuration and control?
- How much does the Consumer need to re-execute to verify that things work?
- How easy is it for the Project to be reused or repurposed by the Consumer?

The key limitation of such an approach is that it is subjective and might lead different people to different conclusions. However, the authors of the framework rightly note that the relationships between the four dimensions are less subjective, and we believe that these can usefully inform product development and optimisation and helpfully explain user choices.

93 RENKU. (n.d.). Collaborative Data Science. **https://bit.ly/3E1mxnt**
94 Nüst, D, Boettiger, C, Marwick, B. (2018). How to Read a Research Compendium. arXiv. **https://bit.ly/2ZeboRz**
95 Zenodo. (n.d.). Research Compendium. **https://bit.ly/3FkgpIp**
96 GitHub Topic: research-compendium. **https://bit.ly/3jnDnVX**
97 Whitehouse, T., Clark, D., & Tsang, E. (2019). Rebooting reproducibility: From re-execution to replication. eLife. **https://bit.ly/3mmxqZW**

In this context, we also highlight that economic disparities can play a role when comparing different technical solutions. Disparities may manifest differently across the world and across stakeholder groups, and may become most apparent in terms of access (or lack thereof) to the Infrastructure components.

The potential impact of FAIR data principles

What we called the 'connectivity problem' is partly enshrined in the 'I' of the FAIR data principles – Findability, Accessibility, Interoperability and Reusability. More broadly, we note that the FAIR principles are highly conducive to reproducible research practices, and the Open Research Europe portal mentions that "by extension, the same practices that enable data reuse also support reproducibility."[98]

Similarly to reproducible publication practices, the practical implementation of FAIR principles tends to be tied to disciplinary considerations: we expect overall progress in this area to follow the policy cycle, too, particularly with regard to the input that different disciplines will need to have in discussing and communicating their needs (see **Figure 3**). In some disciplines, significant progress is being made, for example in the case of the FAIR Cookbook developed for the life sciences[99].

> *"We know that the European Open Science Cloud has a FAIR focus. We know that the Research Data Alliance has a FAIR focus. We know that FAIR is moving into things like software methods. So, there is a broad focus on these among the common interest groups."*
> *Infrastructure provider*

In addition, the thinking around FAIR principles is evolving, noting that "data management planning should be supported across the entire research lifecycle so that data can be "born FAIR" and kept "FAIR enough" over time"[100] – a concept that could be extended to research reproducibility. Although FAIRness and reproducible publication practices are distinct, this strengthens our previous statement that any behaviours involving the management, documentation and sharing of data or code cannot be seen as a simple bolt-on to the research process, even if we only consider the publication stage.

> *"We talk nowadays about data that are 'born FAIR' or 'FAIR by design'. The degree to which you can make your data, or your analytical results FAIR early in the process is going to lead to much higher levels of reproducibility."*
> *Researcher*

In the context of FAIR principles, the European Open Science Cloud (EOSC) also deserves a mention: this initiative is seeking to build "a web of FAIR data and related services",[101] which will reduce fragmentation by federating existing research infrastructures and enhance interoperability between them. It is however important to acknowledge that the EOSC ecosystem is still developing at the time of writing and is therefore not on an equal footing to other digital infrastructures discussed in this report (see also case study on **page 44**).

98 European Commission. (n.d.). Open Research Europe. **https://bit.ly/3uLBR49**
99 Rocca-Serra, P. & Sansone, S, A. (2021). The FAIR Cookbook – a guide for your data FAIRification journey. **https://bit.ly/2YppYoE**
100 FairsFair. (2020). FAIRsFAIR Tables Preliminary Recommendations on Data Policy. **https://bit.ly/3ozGYTZ**
101 Luyben, K. (2021). EOSC: A Web of Fair Data. EOSC. **https://bit.ly/3iBEZLe**

Case study: FAIR data principles and the European Open Science Cloud (EOSC)

In June 2021, the European Commission (EC) and the newly formed EOSC Association **established a Memorandum of Understanding (https://bit.ly/3ixac2b)**, marking the start of the Co-programmed European Partnership on EOSC under the Horizon Europe Framework Programme.

EOSC is seen as the enabling infrastructure that will support "digitally enabled and more open and robust research process not only for scientists, but also for society at large". The Memorandum notes that research objects that are born FAIR will "ensure a true European capacity and global leadership to contribute to the Sustainable Development Goals (SDGs), to reach the EU's ambition for the Green Deal and to implement other national or sectoral policies": this shows the potential impact of FAIR-ness and the significant importance place on this at the European policy level.

According to the **Strategic Research and Innovation Agenda of the EOSC (https://bit.ly/3ae8Jt8)**, "EOSC will deliver a research environment that promotes Open Science and increases trust and reproducibility in research outcomes." Particularly, they note that this developing ecosystem will "provide a sustained and stable infrastructure for research, with a multitude of readily available research datasets and tools, thereby encouraging researchers to develop their own research environment on this platform, encompassing reusing existing components, rather than building one-off, nonreusable tools in their own personal IT space." This is expected to be conducive to reproducible research and publication practices

The signed Memorandum includes a range of "Specific Objectives" (SO4, SO5) and "Operational Objectives" (OO5, OO6, OO8) discussing FAIR data principles and focusing on:

- Increasing the number of publicly-funded research data that are FAIR by design
- Enhancing interoperability between research objects
- Working with communities to develop requirements and practices
- Providing metrics and tools to measure the adoption of FAIR principles
- Co-designing and adopting appropriate rewards and recognitions for the implementation of open data practices

Excursus: Monitoring the reproducibility discourse online

As part of this research, we investigated Twitter data between November 2020 and June 2021. The aims of this exercise were to (i) gauge how the discourse around research reproducibility and good research practices is developing online; and (ii) assess whether any key differences arose between our interview findings and online conversations. Over the above period of time, we have gathered over 10,000 tweets using the hashtags listed in our R notebook and in the footnotes.[102,103]

Our social media analysis shows that the most frequent contributors to the online social media discourse around reproducibility are at the micro level: out of over 30 accounts that tweeted more than 20 times, 12 belonged to individuals and five were from community-led initiatives (e.g. reproducibility networks, training and advocacy initiatives). Interestingly, six of the most prolific accounts were bots, and only one belonged to a research performing organisation (Leiden University Library). This appears to confirm the findings of our literature review and the fact that the recent focus on research reproducibility is mainly developing as a bottom-up movement.

On the other hand, if one looks at accounts in the dataset (i.e. accounts that tweeted at least once using one of the hashtags monitored) with the largest numbers of followers, these include a range of policymakers (e.g. EU DG Research & Innovation, US National Institute of Standards and Technology, Research in Germany), journals and publishers (e.g. Science Magazine, British Medical Journal, Nature Biotechnology), learned societies (e.g. Association for Computing Machinery, Microbiology Society) and news outlets (e.g. Phys.org, LSE Impact Blog). This suggests that meso and macro-level stakeholder groups are, indeed, paying attention, but not leading the discussion – for instance, the top three most followed accounts only had one tweet each in our dataset, while their combined audience was almost 3.5m followers.

Table 5 presents the hashtags included in reproducibility-related discussions. Notably, **Table 5** includes both the hashtags we monitored directly (e.g. #reproducibility and #reproducibleresearch) and other hashtags shared in the tweets we harvested alongside a monitored one (e.g. #openscience). The fact that #openscience – a hashtag we did not monitor – appears so high in the list suggests that reproducibility and open science are very much seen as part of the same whole on social media, too, which once again confirms the outcomes of our stakeholder engagement activities.

102 The hashtags monitored in this exercise included: #Reproducibility, #Replicability, #ReproducibleScience, #ResearchReproducibility, #ReproducibleResearch, #ResearchCredibility, #GoodResearchPractices, #RegisteredReports, #GoodScience, #ResearchCompendium, #ResearchCompendia, #ReproducibilityCrisis, #ReplicabilityCrisis, #ReplicationCrisis and #TuringWay.

103 Chiarelli, A. (2021). Publishing Reproducible Research Outputs - Text and data mining code (Version 2) [Computer software]. Zenodo. **https://doi.org/10.5281/ZENODO.5512019**

Table 5. Hashtags used and occurrences in the dataset. (†=Hashtag monitored)

Hashtag	Occurrences in the dataset	Classification
#reproducibility†	4,148	Key hashtag in reproducibility discussions
#reproducibleresearch†	1,568	Key hashtag in reproducibility discussions
#openscience	1,182	Key hashtag in reproducibility discussions
#methodsmatter	854	Bot-led hashtag
#registeredreports†	481	Chiefly associated with replication
#rrid	350	Bot-led hashtag
#accelerateopenscience	297	Bot-led hashtag
#stmpublishing	270	Bot-led hashtag
#research	204	Generic hashtag
#science	159	Generic hashtag

We note that our data mining exercise was rather broad in scope and included replication-related hashtags too. The only one of these that appeared in the top ten was #registeredreports, while others such as #replicability and #replicationcrisis were only used 121 and 109 times, respectively. Notably, the top 10 also includes four bot-led hashtags: these are most often not tweeted by humans and, to an extent, artificially skew the discussion (but are still less prevalent than the top three). Some generic hashtags are also included in Table 5, but we expect that these will be most effective when used in combination with other reproducibility-focused ones.

Finally, it is interesting to comment on the most mentioned[104] accounts in our dataset, as this can provide an indication of thought leadership and potential impact (see **Table 6**). The Leiden University Library tops the list due to a training seminar on research reproducibility it organised alongside Elsevier. The UK Reproducibility Network is also high in the list, while other reproducibility networks appear at the bottom, likely due to their younger age. It is interesting to note a relatively large number of meso level players in Table 6, including due to training events/advocacy, their role as reproducibility infrastructures or general announcements around the hashtags we monitored.

104 Twitter. (n.d.). About replies and mentions. **https://bit.ly/3Di0aty**

Table 6. Most mentioned accounts (note: Research Consulting, the report's author, appeared as #9 and has been excluded from this table).

Account	Occurrences in the dataset	Type
@ubleiden	43	University library
@ukrepro	38	Community-led initiative
@ElsevierConnect	30	Publisher
@repro4everyone	24	Community-led initiative
@CodeOceanHQ	23	Infrastructure provider
@OSFramework	19	Infrastructure provider
@SciReports	19	Publisher
@protocolsIO	16	Infrastructure provider
@SwissRN	14	Community-led initiative
@GermanRepro	13	Community-led initiative

6. Covering the costs of reproducible publication practices

Identifying funding mechanisms to cover the time and effort underpinning reproducible publication practices is key. Four activities may give rise to costs across a research project: the curation, preparation and sharing of research objects by researchers; the support provided by staff based at research performing organisations; the reproducibility checks executed in the context of the publication process; and any post-hoc reproducibility checks.

Cost implications of reproducible publication workflows

There is a shared view across all stakeholder groups consulted that research reproducibility should be mainly owned by individual researchers: this is largely because they are the ones designing, delivering and publishing their work. Our conversations pointed to the fact that it is extremely difficult (if not impossible) to only consider reproducibility at the publication and dissemination stage: this indicates that, to publish in a reproducible way, researchers would need to consider a range of practices and behaviours throughout the research process.

In this section, we present a range of funding mechanisms to support research reproducibility efforts and related checks, focusing on covering the costs of:

- The time and efforts of researchers in the context of a research project
- The time and effort of research support staff based at research performing organisations
- Reproducibility checks in the context of the publication process
- Post-hoc reproducibility checks

The first of these two bullets is seen as a necessary condition to move research reproducibility up the agenda: to meet an increased level of expectations researchers need acknowledgement and support from their organisations. Without this, research reproducibility may remain a domain-specific or niche activity. On the other hand, further discussion and experimentation is needed with regard to checking and verification activities, including roles and responsibilities and timing (see **section 3**).

It should be noted that, due to the evolving nature of the reproducibility discourse, the mechanisms discussed in this section are somewhat experimental in nature, and that very limited information is available to compare their effectiveness.

Funding the time and efforts of researchers in the context of a research project

A straightforward way to financially support research reproducibility is by directly funding time and other related costs (e.g. infrastructure, subscriptions to software tools or services) in the context of research grants. This is what some funders are already doing with regard to research data management,[105,106] and similar funding mechanisms could be developed to cover reproducibility.

105 OpenAIRE. (n.d.). How to identify and assess Research Data Management (RDM) costs. **https://bit.ly/3Ddnk4r**
106 University College London (UCL). (n.d.). Costing Research Data Management. **https://bit.ly/3iz2rZG**

Some of the funders we interviewed did recognise the importance of funding reproducibility efforts: although no such mechanisms are currently in place, there is an understanding that increased expectations should be met by additional funding.

> *"Foundations accept that this [reproducibility efforts] is a potential future expense – it's even expense today… The only thing that we have required is that it cannot be part of some unspecified, unclear overhead cost."*
> *Research funder*

Accurately estimating the time required to deliver reproducibility-related activities (from project design to publication) is difficult, as these cannot be artificially separated from other good research practices (e.g. ethics, integrity) and open research considerations (open and FAIR sharing of data, code and articles). In addition, differences in time and efforts based on disciplinary customs and research approaches further complicates matters. This suggests that an extent of trial and error will be required before a 'reproducibility costing tool' similar or complementary to those available for research data management[107] can be considered, particularly as the two practices are closely related.

Finally, we note that funding individual researchers or projects via research grants does not address the long-term nature of some aspects of research reproducibility. For example, digital infrastructures and data preservation require different funding mechanisms, as they extend beyond the life of a project and typically serve a much broader audience.

Funding the time and efforts of research support staff based at research performing organisations

Some of our interviewees estimated that reproducibility efforts are unlikely to require one or even half a full time equivalent (FTE) for the entire duration of a project: as a result, principal investigators would most often be unable to hire dedicated staff focusing on this. This is why it would be beneficial for some reproducibility-related activities to be taken over by research support staff at research performing organisations (see **section 4**).

> *"It's very hard for a project to recruit somebody on 0.1 or 0.2 FTE. And nobody is going to go for that sort of position – or it's not an attractive prospect for somebody with good data skills to go for that sort of position, unless they are in particular circumstances."*
> *Research performing organisation*

If some responsibility is allocated to research performing organisations, it is important to consider that university[108] (and library)[109] budgets are under growing pressure, including because of the COVID-19 pandemic. During our consultation, it became clear that funding research support staff in a sustainable manner is difficult but not impossible: for example, research performing organisations may commit to fund a portion of the FTEs of a team of data stewards, data curators or subject librarians (e.g. 20%), and expect the rest (e.g. 80%) to be covered by funded projects. By doing so, research funding organisations would effectively subsidise these positions and mirror their policy commitments (if any) to good research practices and research reproducibility. For research performing organisations to be successful in these efforts, there is a need for a strong strategic commitment from senior leaders and a willingness to start pilot programmes to assess what works in the local context and mix of disciplines.

> *"The university funded a certain number of posts centrally on a per school basis. But the idea was that, within three years, they would be effectively fully recovered cost wise from bids within the school […]. I think 80% of their salary would need to be recovered on a regular basis for the positions to be extended."*
> *Research performing organisation*

107 UK Data Services. (2015). Costing Tool. **https://bit.ly/3lgGwbj**
108 World Bank. (2020). Under Pressure: Covid 19 and funding European Higher Education. **https://bit.ly/3Bit9Ns**
109 Brinton, J. (2021). The impact of COVID-19 on the UK publishing industry: Findings and opportunity. Learned Publishing, 34(1), 43–48. **https://doi.org/10.1002/leap.1363**

Case study: The Data Stewardship programme at TU Delft

In 2017, TU Delft Library initiated a pilot **Data Stewardship (https://bit.ly/2Yqa7G7)** project to comprehensively support research data management requirements across the university. This effort was based on the recognition that "ensuring any lasting cultural change is not just about technology and expertise but, perhaps more importantly, about communication and trust. Relationships between researchers and those who advise them on data management practice need to be developed over time and by allowing people to get to know each other and to work closely together." The Data Stewardship project was **centrally supported via strategic funding (https://bit.ly/3uPKevB)** from the University's Executive Board and co-ordinated by the Data Steward Co-ordinator working from TU Delft Library.

Four years down the road, the pilot initiative has developed as a significant resource for TU Delft, with funding responsibilities being **shifted to individual faculties (https://bit.ly/3oE2Rlk)**. Data steward positions have been made permanent by faculties, recognising their important role in handling data management demands arising across the university.

Between 2020 and 2021, the team of data stewards has had a range of impacts on the university by:

- Supporting over 800 requests from researchers
- Establishing and delivering faculty-specific data management training
- Expanding support at the university level, e.g. by offering a genomic data carpentry workshop, a code refinery workshop and a social science data carpentry workshop
- Implementing faculty-specific data management policies and providing localised and specific guidance to researchers

Overall, the Data Stewardship project **recognised (https://bit.ly/3ah8CN6)** that "community building is essential in changing the code and data management culture" and that Data Stewards can effectively interact with their faculty, the central library, central services and individual researchers. Particularly, the complementary role of **Data Champions (https://bit.ly/3aePgZ4)** is stressed, as "one Data Steward cannot be familiar with all the discipline-specific practices within their faculty, and peer-to-peer learning is more effective".

TU Delft's **Strategic Framework for Data Stewardship (https://bit.ly/3BjEfl4)** notes that "good stewardship of […] data - collecting, documenting, sharing, publishing and preservation - is essential to ensure that scientific arguments and results are reproducible, and that TU Delft is perceived as a trustworthy partner by both public and commercial organisations."

Funding reproducibility checks in the context of the publication process

There are several ways to implement reproducibility checks, corresponding to different stages in the publication process (see **Figure 5**).

Our consultation highlighted in particular the following three pathways:

- Peer reviewers could take on additional responsibilities, by testing articles, data, and code for reproducibility when these are being considered for publication
- Publishers could make available in-house staff such as data or reproducibility editors[110,111]
- Third parties could be tasked with testing articles for reproducibility by authors, journals or funders

The first of these three options is the least likely to be successful, including because peer review is presently an unfunded and unwritten responsibility of researchers. Adding reproducibility-related tasks or requirements to the role of peer reviewers may be opposed by the research community, because this implies a time commitment that not all researchers can afford and additional expertise (e.g. coding) that may not be available to all.

> *"For the peer review, essentially, you often don't have a lot of time to do it. So expecting the peer reviewer to really verify whether everything checks out computationally from a manuscript is, I think, somewhat overburdening."*
> *Researcher*

On the other hand, the second and third bullets provide a better balance between the responsibilities of research stakeholders and, as such, are generally seen as more agreeable.

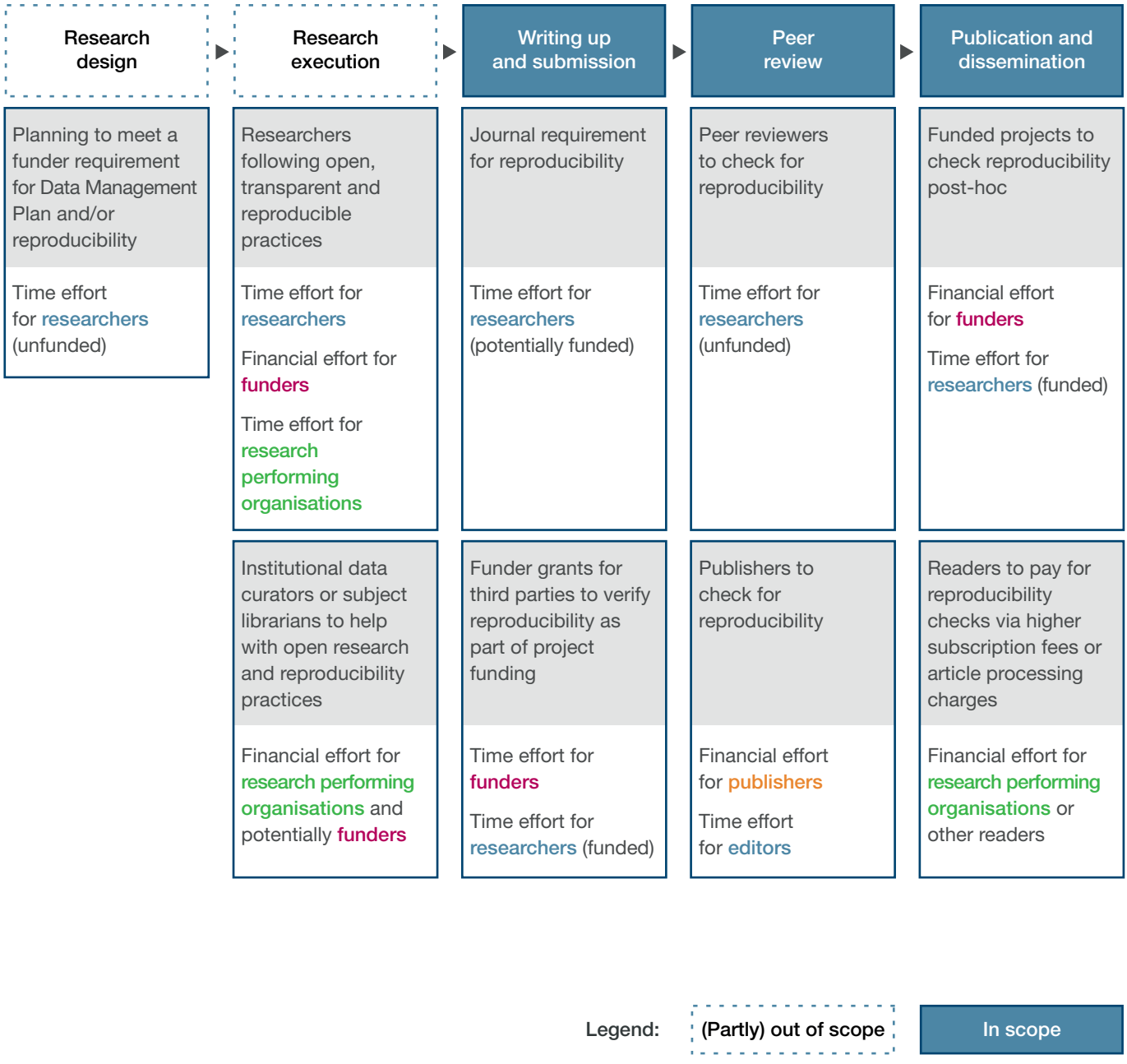
Some of the publishers we engaged noted that journals may fear adding reproducibility requirements to the submission process, but our research showed that some journals have implemented reproducibility checks in their workflows (see **section 3**). In these cases, the role of data or reproducibility editors is key[112,113,114] and this is likely to cover a range of responsibilities such as conformity to guidelines around reproducibility, inspection of research data and code review. It is not entirely clear how these efforts are funded internally by journals, but we found that such responsibilities may be pooled across different titles by a publisher, including in the form of small teams focusing on research data and reproducibility.

> *"In current research there are many, many articles where you're dealing with data that is so big, and so multidisciplinary, that it's not necessarily appropriate for peer reviewers to do it [conduct reproducibility checks]. You can actually only review that sort of information if you reuse the data yourself."*
> *Publisher*

Finally, researchers, publishers or other stakeholders may wish to outsource reproducibility checks. This is somewhat different from other mechanisms, as it reduces some of the effort required from individual researchers, their institutions and publishers and shifts it to other service providers. Of course, this comes at a cost, which one of the stakeholders involved will have to bear.

110 Office of the AEA Data Editor. (2021). Office of the AEA Data Editor. **https://bit.ly/3vwuIFt**
111 Twitter. (2021). Ben Greiner Tweet Status. **https://bit.ly/3niePyr**
112 American Statistical Association (ASA). (n.d.). JASA Editors Talk Reproducibility. **https://bit.ly/2YGDC7e**
113 Elsevier. (n.d.). Information Systems. **https://bit.ly/2X0KJ9P**
114 Biometrical Journal. (n.d.). Biometrical Journal AUTHOR GUIDELINES. **https://bit.ly/2YAmy2U**

Figure 5. Financial efforts, time efforts and research funding models



Quantifying the cost of outsourced reproducibility checks is complex, as these will inevitably vary based on disciplinary requirements and approaches. However, a working paper published in collaboration with the French certification agency cascad[115] comes to the rescue: they modelled the impact of economies of scale on the cost of reproducibility checks and shared insightful findings (see **Table 7**)[116].

Table 7. Estimated set-up and ongoing costs (infrastructure and time) to deliver reproducibility checks (cascad)

Cost category	Type	Estimated cost (€)
IT infrastructure	Set-up	50,000
Cost of accessing data (conservative estimate)	Set-up	5,000
Labour (10 hours per verification)	Ongoing	150 per verification

The research conducted by cascad led to a figure of €320 per article checked, and this estimate may get as low as €155 per article as the number of checks increases and/or the infrastructure costs are amortised over a longer period of time (in this model, costs vary based on the number of 'verification teams', and these figures refer to a case with a single team).

It should be noted that cascad operates mainly in the field of Economics, and the figures discussed above reflect this focus. For example, the authors acknowledge that the review time at cascad may be higher than average due to the need to access confidential data.

Although it is not possible to generalise the costs shown in Table 7, "the costs of [outsourced] verified reproducibility are far from negligible, but still manageable if one strives to reduce implementation costs and finds the right economic model"[116].

Funding post-hoc reproducibility checks

Research funding organisations may make mechanisms available to check published research for reproducibility (see for example the mention of NWO's 'Replication studies' in **section 3**).

It is important to acknowledge that directly funding reproducibility checks is not seen as a sustainable long-term solution, but as an awareness raising tool to socialise the idea of reproducibility and put it under the spotlight. In the long term, funders are more likely (and keen) to provide smaller amounts as part of grants to cover the additional cost of reproducibility-related responsibilities, both throughout the research process and at the time of publication.

> *"In most of our calls, we already allow people to budget specifically for open access publication. And I think [reproducibility practices] are something that could equally be included. In the future, we are hoping to work with a funding system where there are modules that you can request for different aspects of your publication, and [reproducibility] could simply be one of them."*
> *Research funding organisation*

The above is not to say that there is no room for post-hoc verification, but simply that this does not appear to be a practical strategy for research funding organisations. For example, researchers looking to reuse someone else's published work may decide to check whether this is reproducible before moving forward, but as part of their own (and, potentially, funded) workflows.

Finally, at least in principle, funders could play a checking role themselves, focusing on the reproducibility of work published in the context of their grants. However, given the significant difficulties experienced in checking compliance with research data policies[117], it is unlikely that this strategy will be pursued.

115 Cascad. (n.d.) cascad - Certification agency for scientific code & data. **https://bit.ly/3B2YzGw**
116 Hurlin, C., & Perignon, C. (2019). Reproducibility Certification in Economics Research. SSRN. **https://doi.org/10.2139/ssrn.3418896**
117 Couture, J. L., Blake, R. E., McDonald, G., & Ward, C. L. (2018). A funder-imposed data publication requirement seldom inspired data sharing. PLOS ONE, 13(7), e0199789. **https://doi.org/10.1371/journal.pone.0199789**

The cost of digital infrastructures

It might look surprising that our discussion so far has not touched on the cost of digital infrastructures to implement reproducible research publication practices. Our study showed that researchers are already using most of the tools they would need to publish in a reproducible way, such as code repositories, data repositories or specialist software, and access to these is either free at the point of use[118] or paid for by research grants or research performing organisations. In addition, the balance between commercial and public infrastructures is not seen as an issue, as long as researchers have the tools they need to deliver their work and the risk of vendor lock-in is limited (see **section 5**).

> *"If you can somehow guarantee the prevention of vendor lock-in, or at least the closing off of a market by a particular player, then I think we can, in a way, relax about the role of the private sector. I don't think we want to eliminate them; I think they're going to provide the most robust solutions anyway in the end."*
> *Researcher*

Two areas of digital infrastructures, however, may benefit from increased or new funding:

- Efforts to strengthen and improve the capability of existing infrastructures needed **at the publication stage**: we found that the tools available in the landscape are often fit for purpose, but an increase in open research practices and sharing will require improved features and capabilities (e.g. data storage, speed of access, digital preservation)
- Efforts to develop additional digital infrastructures providing reproducibility-related functionality **across the research process**, including enhancing interoperability and better embedding solutions in existing workflows: this type of solution is currently being designed and trialled in different disciplinary domains, focusing on tracking and describing research objects as a project evolves

Although the second bullet is slightly beyond the scope of this report, it is worth discussing in more detail. Due to the early stage of development and significant experimentation, the efforts to support reproducibility across the life of a project are not yet financially sustainable, even if they are perceived to be viable and desirable by some disciplinary communities[119]. In these scenarios, research funding and research performing organisations may play a role in providing financial support in the short-to-medium term, to ensure that innovative research workflows focusing on reproducibility and transparency are considered and implemented. This, for example, is the funding model adopted by Renku, which is supported by the Swiss Data Science Center (a joint venture of EPFL and ETH Zurich), and by the CONQUAIRE (Continuous Quality Control for Research Data to Ensure Reproducibility) project at the University of Bielefeld, which was supported by German funder DFG and sought to develop services and tools for researchers to use when creating/collecting/versioning data and making it reusable[120]. A more recent example is offered by the Octopus platform, which was awarded £650,000 by UKRI and seeks to "provide a new 'primary research record' for recording and appraising research "as it happens'"[121].

Finally, we highlight the benefits of facilitating conversations between academic-led efforts to develop digital infrastructures and commercially-savvy individuals or organisations (unless the two overlap). The former will

118 We note that many services are free to use at the time of writing, for example Zenodo, the OSF or GitHub. However, their funding models may need further consideration in the future to ensure long-term sustainability.
119 Black, S., Gardner, D, G., Pierce, J, L., & Steers, R. (2019). Organisational Behaviour. **https://bit.ly/3AwwiYP**
120 Ayer, V., Wiljes, C., Cimiano, P., Pietsch, C., Vompras, J., Schirrwagen, J., & Jahn, N. (2017). Conquaire: Towards an Architecture Supporting Continuous Quality Control to Ensure Reproducibility of Research. D-Lib Magazine, 23(1/2). **https://doi.org/10.1045/january2017-ayer**
121 Anderson, R. (2021). "Positively Disrupt(ing) Research Culture for the Better": An Interview with Alexandra Freeman of Octopus. The Scholarly Kitchen. **https://bit.ly/3oNvtsb**

have in-depth knowledge and understanding of their audience and pain points, while the latter can contribute strategies for large-scale deployment, sustainable business growth and product-market fit. These discussions are important regardless of whether a tool or service is developed as a for-profit or not-for-profit, particularly in cases where funding has been provided for the start-up/pilot phase only and no long-term plans are in place.

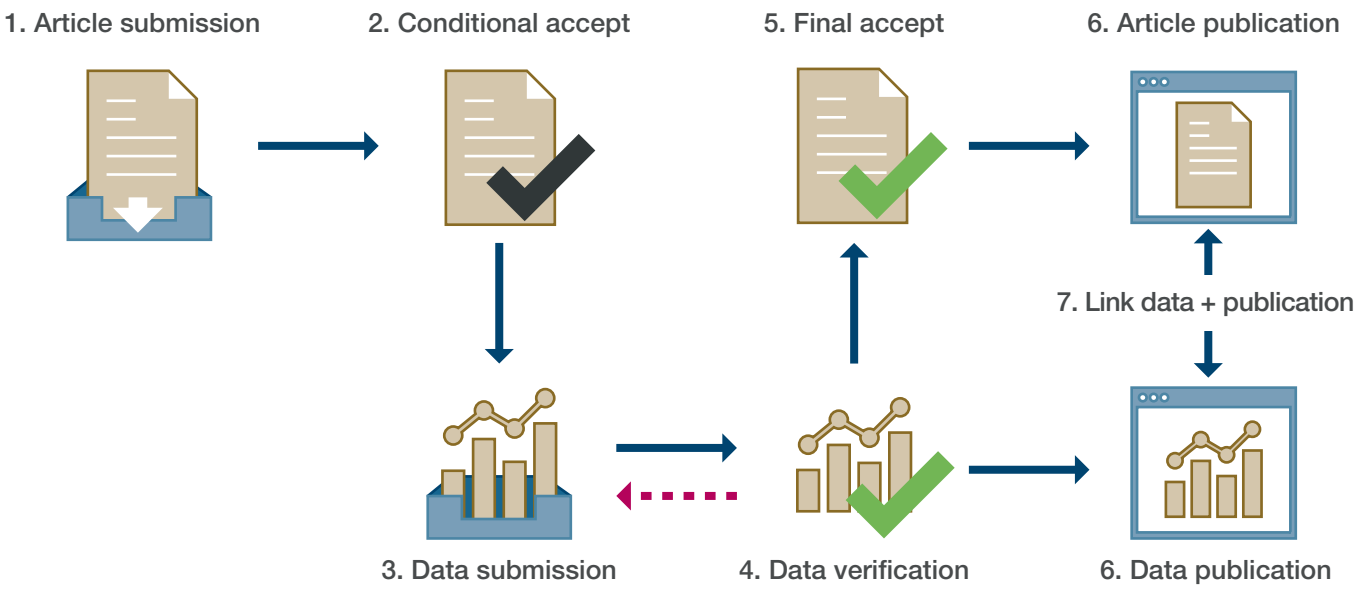
As noted previously, we did not investigate non-digital infrastructures. We do, however, recommend that their needs are monitored in the future, as funding requirements may arise as the reproducibility discourse continues to develop.

Complexities in monitoring compliance

Although a wide range of technological solutions are in place to support reproducible publication practices and a range of business models are available, this does not mean that monitoring and enforcing reproducibility requirements will be straightforward.

It is helpful to draw on experiences in the open and FAIR data landscape, where several requirements are being set by funders and, to a lesser extent, publishers[122,123]. In these cases, there is a significant gap in terms of enforcement: although policies and workflows are in place (see **Figure 6** for a sample workflow covering data reviews), the cost of enforcing them and monitoring compliance is often too high to be practicable. Checking reproducibility requirements requires an even more complex review of connected research objects, including an understanding of (sub)disciplinary matters: as a result, it may be difficult for funders to take on this type of monitoring responsibility.

Figure 6. Sample data review and verification workflow by an academic journal (CC BY Christian et al.)[123]



122 Stodden, V., Seiler, J., & Ma, Z. (2018). An empirical analysis of journal policy effectiveness for computational reproducibility. Proceedings of the National Academy of Sciences, 115(11), 2584–2589. https://doi.org/10.1073/pnas.1708290115

123 Christian, T.-M. L., Lafferty-Hess, S., Jacoby, W. G., & Carsey, T. (2018). Operationalizing the Replication Standard. A Case Study of the Data Curation and Verification Workflow for Scholarly Journals. International Journal of Digital Curation, 13(1), 114–124. https://doi.org/10.2218/ijdc.v13i1.555

> *"Funder policies are helpful, but I'm not sure they're effective… The funder typically doesn't check whether or not you did what you said you were going to do, and without that checking there's a lot of scope for people simply not doing it."*
> *Researcher*

The timing of compliance checks, which we covered earlier in this section, is also key. Checks after the submission of an article require peer reviewers and/or editors to carefully assess a series of research objects, including whether the appropriate mix of resources has been submitted in the first place: this may be difficult because of time pressures, in the case of reviewers, and disciplinary knowledge gaps, in the case of editors.

> *"It's rapidly becoming the case that we will need specialised people who have a full understanding of what it means to make data and code accessible and reproducible."*
> *Publisher*

On the other hand, post-hoc compliance (i.e. after publication) is, in many cases, too late in the publication process: although it may have value as a means of increasing awareness about reproducibility, it is unlikely to be a significant compliance tool in the long run.

As this report focuses on reproducible publication practices, we have not sought to discuss ex-ante checks (i.e. tests by authors or other colleagues during the research process and before submission of the article). For completeness, we note that ex-ante checks can be implemented in a wide range of ways, e.g. code review within one's research group, reproducibility checks by external peers or the sharing of preprints – a practice that has been significantly growing in popularity over the past ten years[124,125,126].

> *"I think one of the ways to ensure reproducibility is to make sure that errors are detected as early on as possible, and the good thing about detecting an error at the preprint stage is that you can correct it before it gets into the version of record of submission to a journal."*
> *Researcher*

124 Puebla, I. (2020). Preprints: a tool and a vehicle towards greater reproducibility in the life sciences. Journal for Reproducibility in Neuroscience, 2. **https://doi.org/10.31885/jrn.2.2021.1465**

125 Baker, S (2021). Has the Pandemic Changed Research Culture- and is it for the better? Times Higher Education. **https://bit.ly/3BvfGIt**

126 Chiarelli, A., Johnson, R., Pinfield, S., & Richens, E. (2019). Accelerating scholarly communication: The transformative role of preprints. Zenodo. **https://doi.org/10.5281/ZENODO.3357727**

7. Conclusions

Reproducible publication practices are developing as part of a broad process of cultural change across the research landscape. However, this ongoing evolution is slow in comparison to the rapid technological innovation that we are witnessing. Overall, we expect that researchers will be ready to adopt reproducible publication practices, as long as a balance is found between increasing expectations, practical rewards and fit-for-purpose infrastructure, and provided that diversity is considered as a guiding principle.

The (im)balance between technical and cultural infrastructure

Our work on reproducible publication practices paints an optimistic yet complex picture. We have found that the technologies needed to enable reproducible publication are mostly available and that all stakeholder groups are alert to the topic. At the same time, we heard two strong messages:

- Research reproducibility should not be considered only at the publication stage, mainly because of data/code preparation and curation concerns, but also because it requires an overarching framework of reward mechanisms, support structures and funding
- Research reproducibility is part of a much broader discussion around open science and would be very difficult to pursue as a separate consideration from other good and open research practices

Our research brought to light a visible imbalance between cultural and technical infrastructures, showing that the former are lagging behind due to the above-mentioned point that reproducibility is evolving as part of a much broader movement (see **Table 8**). Our consultation highlighted practical solutions and ideas to support reproducible publication practices, which are most often technical in nature, alongside the complexity of cultural change, which is a long-term process and cannot be as tightly constrained as our current scope of work.

Table 8. Imbalance between cultural and technical infrastructures

Dimension	Key considerations
Technical infrastructure	▸ Focus on specific research objects and workflows ▸ Technical, relatively straightforward implementation ▸ Lack of service/tool interoperability ▸ Significant level of experimentation
Cultural infrastructure	▸ Reproducibility is part of a much wider process of cultural change ▸ Interrelations with replication and other neighbouring concepts, including some overlaps in terms of definitions, cultures and workflows

The vision for reproducible publication practices

Researchers are perceived as wanting to work and publish in the best possible ways and are assumed to already work to the best of their abilities and respect quality, ethics and integrity requirements. As a result, we expect that they will be happy to pick up reproducible publication practices as long as the system within which they operate provides the right mix of support, reward and recognition.

Project contributors described reproducible publication practices as being highly desirable for the future of science: provided that a "shame and blame" culture is avoided, all stakeholders consulted felt that this is a worthy direction of travel that will lead to enhanced collaboration, accountability and information sharing across the board. We have, however, identified four strategic roadblocks that are expected to hinder future efforts: these are discussed throughout our report and summarised in **Table 9**. Some of these roadblocks are structural in nature (e.g. roles and responsibilities, familiarity with research data), while others are more operational and can be resolved with an extent of experimentation and compromise (e.g. training and support provision, business models).

Table 9. Practical roadblocks to reproducible publication practices

Research data management practices have not yet been widely adopted, which hinders the uptake of reproducible research workflows.	**Checklists, guidelines and standards for reproducible publication need to be developed.**
To enable the publication of reproducible research outputs, some form of data sharing (whether publicly or not) is required. Practices, requirements and rewards for research data management remain immature in many domains, which makes reproducible publication difficult to achieve across the board.	Funders and publishers do not think they are in a position to impose detailed requirements for communities and disciplines, as they tend to operate at a higher level. There is a need for communities and disciplines to share their requirements with stakeholders at the meso and macro level so that these can be reflected in policies, checklists, guidelines and standards.
Business and funding models to cover the costs of reproducible research publication are currently experimental and rare.	**Training on reproducible publication is complex, and the locus for support is unclear.**
Although some funders do cover the costs of data curation and sharing, reproducible publication introduces additional requirements. At present, NWO is the only funder explicitly covering reproducibility efforts, but this is not seen as a long-term approach. Further consideration is needed, but the present report does provide a range of starting points for future discussions around business models.	Training and support responsibilities for reproducible publication practices currently fall on a broad range of stakeholder groups, including learned societies, research performing organisations and publishers. Within research performing organisations, the creation of roles such as data stewards, data curators or subject librarians may help, but this requires a strategic commitment from senior leaders.

Today, the biggest practical obstacle to reproducible publication is that, in some disciplines, the concept of data sharing is still somewhat misunderstood (particularly some branches of qualitative humanities and social sciences, but with some notable exclusions such as economics or psychology). In these cases, sharing 'data' to validate one's publications is a big and partly premature ask.

Driving change

Our research strongly points to the fact that research communities and disciplines will have to play a role in communicating their needs, which will help ensure that new expectations are grounded into the reality of their everyday research practices. A policy cycle interpretation (see **Figure 3**) makes it clear that this is a necessary condition to move towards policy implementation, enforcement and evaluation.

The other side of the coin is that researchers across the disciplinary spectrum will not be intrinsically motivated to contribute to these efforts unless they see and experience the benefits of reproducible publication practices. We believe that research funding organisations can play an important role in enabling further conversations, in the first place by considering and rewarding reproducibility-related considerations in the context of grant applications. In addition, funding mechanisms (potentially at the international level) could support broad disciplinary consultations to help develop checklists, guidelines and standards that work for most (e.g. covering the appropriate range of research objects in each discipline). Ideally, practical and tailored policies should grow organically from the bottom up and be firstly adopted by journals and infrastructure providers, and, subsequently, generalised and implemented by research funding organisations and policymakers.

In addition, it is broadly understood that research funding organisations and publishers have the potential to drive compliance when it comes to reproducible publication practices. The former can drive requirements and research practices via their policy requirements, while the latter can implement checklists, guidelines and standards for authors, editors and peer reviewers. Ideally, it would be beneficial if funder and journal requirements could grow hand-in-hand, at least to an extent. For example, some journals may worry that making their requirements too strict might deter author submissions: developing requirements in a concerted way could help ensure alignment between policies and expectations with regard to reproducible publication practices.

We wish to stress that there is a risk for policies and their enforcement to leave little room for nuance. For some epistemic cultures, for instance, reproducibility will be harder to understand and implement, or perhaps is not even the goal; in others, reproducibility may not be seen as the key quality hallmark, but just as an option among many. It will therefore be necessary to consider diversity as we rethink research practices to preserve and boost trust in science.

Overall, we believe that our findings paint a cautious yet optimistic picture: by engaging with the obstacles identified and leveraging the opportunities available, there is significant room for reproducible publication practices to play a prominent role in the ongoing shift to open science.

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Appendix A – Acknowledgements and participants

Table A1: Knowledge exchange task and finish group on publishing reproducible research output

Name	Affiliation	Role	Country
Anna Mette Morthorst	Danish e-infrastructure cooperation (DeiC)	Special Consultant	Denmark
Birgit Schmidt	University of Göttingen	Head of Knowledge Commons	Germany
Birte Christensen-Dalsgaard	Aarhus University	Chief Consultant	Denmark
Daniel Nüst	University of Münster	Researcher	Germany
Jeroen Sondervan	Utrecht University	Publishing Consultant	Netherlands
Juliane Kant	Deutsche Forschungsgemeinschaft (DFG)	Programme Officer, Scientific Library Services and Information Systems	Germany
Matt Jaquiery	University of Oxford	Researcher	UK
Pierre-Carl Langlais	Paris Sorbonne-CELSA	Associate researcher	France
Saskia Woutersen	Leiden University	Digital Scholarship Librarian	Netherlands
Verena Heise	Independent	Open Science researcher, trainer and consultant	Germany
Yrsa Neuman	Åbo Akademi University	Chief Coordinator of Responsible Research/Open Science	Finland

Table A2: Project contributors

Name	Affiliation	Role	Country
Alexandra Freeman	Winton Centre for Risk and Evidence Communication, University of Cambridge	Executive Director	United Kingdom
Amy Orben	University of Cambridge, founder of ReproducibiliTea	Fellow	United Kingdom
Andreas Bleuler	Swiss Data Science Center Renku	Senior computer scientist	Switzerland
Anita Bandrowski	UC San Diego SciScore	Specialist, Neurosciences	United States

Name	Affiliation	Role	Country
Bart Penders	Maastricht University	Associate Professor	Netherlands
Bertram Ludaescher	Center for Informatics Research in Science and Scholarship, University of Illinois at Urbana-Champaign Whole Tale	Director, Professor	United States
Brian Nosek	Center for Open Science	Co-founder, Executive Director	United States
Carlien Hillebrink	Dutch Research Council	Policy advisor	Netherlands
Carsten Bergenholtz	Aarhus University	Associate professor	Denmark
Catherine Bromley	Economic and Social Research Council	Deputy Director of Data Strategy and Infrastructure	United Kingdom
Catriona MacCallum	Hindawi	Director of Open Science	United Kingdom
Christophe Perignon	HEC Paris	Professor of Finance, Associate Dean for Research	France
Daniël Lakens	Eindhoven University of Technology	Associate professor	Netherlands
Emma Ganley	Protocols.io	Director of Strategic Initiatives	United States
Erik Schultes	GO FAIR International Support and Coordination Office	International Science Coordinator	Netherlands
Gordon Feld	Central Institute of Mental Health	Head of the Psychology and Neurobiology of Sleep and Memory Research Group	Germany
Heidi Seibold	Johner Institut	Research team member	Germany
Jana Lasser	TU Graz	Postdoctoral researcher	Austria
Jean-Sébastien Caux	University of Amsterdam SciPost	Professor, Chairman of Scipost	Netherlands
Jennifer Gibson	Interviewed in her role at eLife, currently at Dryad	Former Head of Open Research Communication (eLife) Executive Director (Dryad)	United Kingdom
Karel Luyben	EOSC Association Delft University of Technology	President of the EOSC Association, Rector Magnificus Emeritus	Netherlands
Katja Mankinen	CSC – IT Center for Science	Data scientist	Finland
Kelly Lloyd	University of Leeds	PhD Student	UK
Kristina Hettne	Leiden University Libraries	Digital Scholarship Librarian	Netherlands

Name	Affiliation	Role	Country
Ksenija Bazdaric	Rijeka Faculty of Medicine European Science Editing	Assistant Professor at the Department of Medical Informatics Chief Editor	Croatia
Liz Bal	Jisc	Director of Open Research Services	United Kingdom
Lorena Barba	George Washington University	Professor of Mechanical and Aerospace Engineering	United States
Malvika Sharan	The Turing Institute	Community manager	United Kingdom
Marcus Munafò	University of Bristol	Professor	United Kingdom
Mari Riipinen	University of Turku	Head of Research Development Unit	Finland
Marin Dacos	French Ministry of Higher Education, Research and Innovation	Open Science Advisor	France
Mark Hahnel	Figshare	Founder, CEO	United Kingdom
Martina Grunow	Leibniz Information Centre for Economics	Project Manager (Publication Services)	Germany
Martine Garnier-Rizet	Agence nationale de la recherche	Head of Digital technology and Mathematics Department	France
Mary Donaldson	University of Glasgow	Service Coordinator (Research Data Management Service)	United Kingdom
Matti Ruuskanen	University of Turku	Postdoctoral researcher	Finland
Philipp Cimiano	Bielefeld University	Professor, Head of the Semantic Computing Group	Germany
Philippe Bonnet	IT University of Copenhagen	Professor	Denmark
Rémy Mosseri	Centre national de la recherche scientifique	Scientific Integrity Officer	France
Rik Henson	British Neuroscience Association	President Elect	United Kingdom
Sarah Callaghan	Patterns - Cell Press	Editor-in-Chief	United Kingdom
Simone Sacchi	European University Institute	Open Science Librarian	Italy
Sonja Ochsenfeld-Repp	Deutsche Forschungsgemeinschaft (DFG)	Head of Division - Equal Opportunities, Research Integrity and Cross-Programme Development	Germany
Sven Vlaeminck	Leibniz Information Center for Economics	Project manager (Research data)	Germany
Tim Smith	CERN Zenodo	Head of Collaboration, Devices and Applications Group, Zenodo Steering board member	Switzerland
Tyler Whitehouse	Gigantum	Co-founder, CEO	United States

Name	Affiliation	Role	Country
Ulrich Dirnagl	Charité – Universitätsmedizin Berlin	Director of the Department of Experimental Neurology	Germany
Ulrik Nicolai de Lichtenberg	Novo Nordisk Foundation	Senior Scientific Manager	Denmark
Valerie McCutcheon	University of Glasgow	Research Information Manager (Library Services)	United Kingdom
Vicky Rampin	New York University	Research Data Management & Reproducibility Librarian	United States
Victoria Moody	Jisc	Director of Research and Innovation Sector Strategy	United Kingdom

Appendix B – Interview questions

This appendix includes a list of interview questions used for the purposes of this study. Questions were asked based on stakeholder groups and time availability, meaning that not all questions were asked to all interviewees.[127]

Legend:

- RFO: Research Funding Organisations
- RPO: Research Performing Organisations
- IP: Infrastructure Providers
- AP: Academic Publishers
- RRG: Researchers and research groups

Interview question	RFO	RPO	IP	AP	RRG
To what extent is our definition of reproducibility familiar to you? Are you aware of any other ways the term is used?	✓	✓	✓	✓	✓
For what reasons should the research community consider reproducibility as part of everyday research practices?	✓	✓	✓	✓	
Do you perceive a need for action when it comes to research reproducibility, particularly at the publication stage?	✓				✓
How are you as a funder addressing research reproducibility in your policies?	✓				
What rewards and incentives could be conducive to reproducible research practices?	✓	✓		✓	✓
Who should be responsible for reproducibility checks, and at what stage in the submission, review and publication process?	✓	✓	✓	✓	✓
How can funders enable and monitor reproducible research practices against their policies?	✓				
What business models might be appropriate to cover the costs of reproducibility? (e.g., from "researcher pays" to "funder pays")	✓	✓		✓	✓
To what extent does the community need public infrastructures supporting reproducibility, given that commercial services/journals are developing their own solutions?	✓			✓	✓
Do you see reproducibility as a desirable long-term goal?	✓	✓	✓	✓	✓
Are researchers aware of the range of tools they can use to enable the publication of reproducible research outputs?		✓	✓		
How did you develop your offering around reproducibility? For instance, how did you identify and scope out requirements?			✓		
Are any features or technical solutions to enable reproducibility missing in the current research infrastructure?		✓	✓	✓	✓
Are you aware of the FAIR principles, and does your infrastructure adhere to these?			✓		

127 Chiarelli, A., & Loffreda, L. (2021). Publishing Reproducible Research Outputs - Interviewees and interview questions (Version 1) [Data set]. Zenodo. https://doi.org/10.5281/ZENODO.5141665

Interview question	RFO	RPO	IP	AP	RRG
What is your current funding model and how sustainable is it?			✓		
How do you see the reproducibility landscape evolving in terms of services available to end users? Will these come mainly from commercial services/ journals or from public infrastructures?		✓	✓		
What do you think is the role of publishers with regard to reproducibility? Please consider the role of editors as well as the role of publishers as infrastructure providers.				✓	
Which (potentially new) roles are needed enable the reproducibility checks of manuscripts?				✓	
Which tools or infrastructures are you aware of when it comes to reproducibility?				✓	
Is your institution as a whole interested in research reproducibility?		✓			
To what extent are the links between existing tools and software used by researchers affecting the publication of reproducible research outputs?		✓			
Are researchers being provided with the appropriate level of training and support they need to both publish in a reproducible way and to check other people's work for reproducibility?		✓			
Is your organisation concerned about the potential risks arising from a broader uptake of data and code sharing practices? (e.g., sharing of sensitive or confidential information).		✓			
How do you see the reproducibility landscape evolving in terms of services available to end users? Will these come mainly from commercial services/ journals or from public infrastructures?		✓	✓		
To what extent are your peers and collaborators aware of research reproducibility, particularly at the publication stage?					✓
To what extent are current efforts around research reproducibility sufficient to drive change? Please consider any stakeholder groups that you see as important.					✓
What needs to change in the research process to pay the costs associated with reproducibility? e.g. slower research, more funding, larger research teams, cutting back some other (specific) aspect of research...					✓
What do you feel are the main and most important developments with regard to reproducibility at the publication and dissemination stage? Please consider both technological and cultural developments.					✓
Who do you see as the main driver of innovation around reproducible research practices?					✓
What do you see as the main barriers to the publication of reproducible research outputs?	✓	✓	✓	✓	✓
Are you being provided with the appropriate level of training and support you need to both publish in a reproducible way and to check other people's work for reproducibility?					✓

Interview question	RFO	RPO	IP	AP	RRG
Are you aware of the range of tools you can use to enable the publication of reproducible research outputs?					✓
Do you require grant applications to include any information on reproducibility in the planned project and previous projects? If yes, how is this assessed?	✓				
For example, is this mentioned within open science, open access, or open data policies? What about your research integrity policy?	✓				✓
Do you think that reproducibility could or should be a reason for article rejection?	✓	✓	✓	✓	✓
To what extent is post-publication compliance monitoring required?	✓		✓	✓	
To what extent is there scope for research funding to cover reproducibility practices (similarly to research data management funding)?	✓				
Would you pay for infrastructure costs (e.g. servers, people who maintain infrastructure) directly (rather than through grant funding)?	✓				
Are you thinking about developing or have you developed your own infrastructure supporting open science and reproducibility? If so, how is this funded, and are researchers required to use it?	✓				
Academics may use commercial platforms where these are available. Is this a concern to you as a funder?	✓				
What is the long-term vision for research reproducibility, and what happens once reproducible publication practices are mainstream?	✓	✓	✓	✓	✓
What is the mission of the service you provide, and what are your reasons for providing it?			✓		
Does your platform have a significant uptake? Are there any ballpark statistics you might be able to share with us?			✓		
Are any disciplines or countries particularly popular/common on reproducibility infrastructures?			✓		
How could services available to researchers be better integrated? For example, how could reproducibility solutions and workflows be embedded in today's everyday academic practices?			✓		
What are the overlaps between research data management and reproducibility infrastructures?		✓	✓		
Are some outputs easier to publish in a reproducible way than others? Are you aware of any examples of specific challenges?			✓	✓	✓
In what ways could published research be made easier to check for reproducibility?			✓	✓	✓
Are you aware of executable research articles, and what is their value?			✓	✓	
What funding sources have you considered/secured in the past? What are your expectations/needs in the future?			✓		
What percentage of your current editors would you expect to quickly adopt new workflows to support evaluation of reproducibility?				✓	

Interview question	RFO	RPO	IP	AP	RRG
In what ways could the sharing of supporting materials be rewarded? E.g. computer code, data.				✓	
What infrastructures do you rely on for supplemental data and code, regardless of reproducibility?				✓	
Do you expect researchers to adhere to reporting guidelines? And do any guidelines for your journals include information on reproducibility?				✓	
Do you have a sustainable business model behind your reproducibility efforts?				✓	
More broadly, how do you support open science/reproducible research across your organisation (infrastructure, education, support staff, etc.)?		✓			
Which ones do you have in place for your staff at the moment?		✓			
Is reproducibility part of ethics review procedures for studies that need review?		✓			
How do you ensure uptake of reproducible practices among your researchers?		✓			
What proportion of academics do you see as actively engaging with research reproducibility? Do you see any variation within your organisation and more broadly within your discipline?					✓
Where do you think your research field currently stands compared to other fields?					✓
Are the current policies of research funding organisations and research performing organisations effective with regard to reproducibility?					✓
For example, is this mentioned within open science, open access, or open data policies? What about your research integrity policy?	✓				✓
Which attempts to shift current culture are you aware of? Which worked/failed?					✓
Do you see these developments as incremental or ground-breaking?					✓
Do you feel that these stakeholders are working together and making joint efforts, or are they working in silos?					✓
What do you think might be the benefits of publishing research in a reproducible way?					✓
Is research reproducibility a frequent discussion topic between you and your peers or collaborators? What about your discipline more broadly?					✓
What types of guidance could help you and your peers comply with reproducibility expectations, for example from journals or funders?					✓
For example, what is your level of awareness of research compendia and executable research articles?					✓
When you act as a peer reviewer, what information could help you assess the reproducibility of a manuscript?					✓

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