A Review of the UK's Interdisciplinary Research using a Citation-based Approach

Report to the UK HE funding bodies and MRC by Elsevier

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Executive Summary & Key Findings

Elsevier has conducted a review of interdisciplinary research in the UK in 2009-2013. The report was commissioned by the UK higher education funding bodies and the Medical Research Council (MRC).

Interdisciplinary research (IDR) is often believed to have great potential to contribute to research breakthroughs, address societal problems, and foster innovation. Conceptually we use IDR as a broad term that is inclusive of multidisciplinary, interdisciplinary and transdisciplinary research.

As a national effort to assess the quality of research produced by the UK's higher education institutions, the Research Excellence Framework (REF) plays a key role in the UK's future research policy design and funding allocations. An underpinning principle of the REF is that all forms of research output across all disciplines, including IDR, are assessed on a fair and equal basis.

This project will feed into the broader evaluation work of the REF by providing contextual information on the UK's interdisciplinary landscape within which the funding bodies will be able to consider the REF data.

We use a citation-based approach to identify IDR and measure interdisciplinarity. The basic principle behind our approach is that, if an article cites papers that are "far away" from each other in terms of their topics, it is likely to be interdisciplinary. Otherwise, it is likely to be a monodisciplinary article. Our measure of IDR is a score based only on the research output and does not take into consideration the underlying processes of knowledge integration in cross-discipline research.

The advantage of our approach is the lack of reliance on any pre-defined subject classification to define interdisciplinarity, and is flexible enough to capture the dynamics of the research landscape in which subjects are constantly emerging and changing. We however also recognise the limitations of the approach when looking at a subset of the research outputs produced by the UK, in particular the publications in the research domain of the Humanities.

Using this method, we are able to calculate a measure of interdisciplinarity for 78% of all publications in Scopus in the period 2009-2013. The percentage is in general lower for the Humanities, and to a lesser extent for Social Sciences, Computer Science and Engineering. Publications are ordered according to their IDR scores, and a threshold is set at the 90th percentile to obtain the top 10% IDR worldwide: the 10% of publications with the highest measure of interdisciplinarity. In the report, we compare these publications in the top 10% IDR to all publications with an IDR score, using various indicators such as citation impact, download and patent citation frequency, and the extent of collaboration.

Our results lead to three main conclusions:

- Emerging countries that have grown their research output rapidly such as China and Brazil have a higher share of IDR publications out of their total research output.
- IDR is associated with a lower citation impact overall, but a higher level of citations in patent applications.
- IDR is correlated with lower levels of international collaboration, but the strength of its association with industry collaboration depends on the contextual situation of each country.

In 2009, 7.9% of all UK publications with an IDR score belonged to the world's top 10% most interdisciplinary publications. The percentage increased to 9.1% in 2013, implying a growing intensity of IDR among UK publications. This trend can also be found in all comparator countries.

China and Brazil lead all comparator countries on this indicator from 2009-2013. In 2013, 12.3% and 11.0% of China and Brazil's publications, respectively, belong to the world's top 10% IDR papers.

Both the UK's overall and the UK's top 10% IDR publications are of high quality as indicated by citation impact. In 2013, the field-weighted citation impact (FWCI) of all of UK's publications with an IDR score is 1.71, and that of the UK's publications that belong to the world's top 10% IDR is 1.35. Both measures are the highest among all comparator countries and are much higher than the world average FWCI of 1.

For all comparator countries including the UK, the FWCI of the publications that belong to the top 10% IDR is lower than that of all publications with an IDR score in the period 2009-2013. This suggests that the most interdisciplinary research has a lower citation impact than other publications.

There are many plausible reasons that IDR is associated with lower citation impact. The field-normalized citation measures may be more precise for monodisciplinary publications than for the interdisciplinary ones. Barriers to conducting IDR may play a role in preventing the integration of knowledge from multiple disciplines and attracting the best researchers to conduct IDR. Additionally, citing behaviour may differ for IDR publications, and therefore it takes longer for IDR's impact and value to be recognized. Testing these plausible reasons goes beyond the scope of this report and will require further research.

Despite their lower overall citation impact, IDR publications are cited more frequently in patent applications for many of the comparator countries. For example, in 2013, Germany's publications with an IDR score are cited 1.71 times more frequently in patent applications than the world average, and Germany's world's top 10% IDR publications are cited 2.24 times more frequently. One possible explanation that deserves further investigation is that IDR may often represent applied research, reducing barriers associated with the application of research to industry needs and problems.

There are strong correlations between whether a publication is an international collaboration and the citation impact of that publication. Both the UK's overall and the UK's top 10% IDR publications are highly international. In 2013, around half of the UK's publications with an IDR score involve at least one author outside of the UK. However, among the UK's publications that belong to the world's top 10% IDR, a lower percentage can be classified as international collaborations (45.5%).

For Germany and Japan, the top 10% IDR publications more often involve academic-corporate collaboration than the overall publications. For the UK in the period of 2009-2013, around 4.9% of all publications with an IDR score involve collaboration with industry. The number drops slightly to 4.7% when restricting to publications that belong to the world's top 10% IDR.

Our data and analysis provide contextual information about IDR in the UK and comparator countries. More research is needed to investigate the underlying causes that lead to conclusions in this report. Combining our conclusions and the causes will be essential for deriving policy advice for research managers, funding bodies, and policy makers about barriers to conducting IDR and how to reduce them, and whether there is need for IDR to go beyond the borders of any one institution, country, or sector in order to achieve high citation impact.

Key Findings

SHARE OF UK PUBLICATIONS IN WORLD'S TOP 10% IDR

9.1%

FWCI OF UK PUBLICATIONS IN WORLD'S TOP 10% IDR

1.35

INTERNATIONAL COLLABORATION OF UK PUBLICATIONS IN THE TOP 10% IDR

45.5%

Preface

Elsevier is proud to be commissioned by the UK higher education funding bodies and the Medical Research Council (MRC) to conduct a citation-based review of the UK's interdisciplinary research (IDR) and compare it to eight comparator countries based on the analysis of publication and citation data in the period 2009-2013.

The purpose of this report is to feed into broader evaluation work of the Research Excellence Framework (REF). The report will provide contextual information on the UK's interdisciplinary landscape within which the funding bodies will be able to consider the REF data.

The importance of interdisciplinary research was highlighted in the recent Triennial review of the research councils. The review noted a perception that it was more difficult to win support for multi/inter/cross disciplinary research from the research councils, although the evidence for this was anecdotal.

Whether interdisciplinary research is adequately supported by the research councils is also a question to be addressed in the recently announced review of the research councils led by Sir Paul Nurse.

There are no accepted definitions or measures of disciplinarity which could be used to track changes in success rates, demand for funding or other changes in UK research. The Research Councils are therefore interested in methodology for measuring the 'disciplinarity' of research projects/programmes to support a better understanding of the levels in interdisciplinary research in the Research Councils portfolios, benchmarking with other organisations/countries etc., and also the possibility to investigate some of the perceptions around the funding of interdisciplinary research.

Elsevier hopes that this review will provide the customers with a deeper understanding of the UK's IDR, and will contribute to their strategic decision-making. We however recognise that a citation-based approach may limit the analysis from providing comprehensive understanding for some disciplines, e.g., Arts and Humanities and some disciplines in Social Sciences.

Contents

Introduction and Literature Review

1. Finding solutions for many of the pressing issues the world is facing today reaches beyond the boundary of one academic discipline. The study of climate change for instance requires understanding of the complexity of nature (e.g., oceans, seas, rivers, energy, land, air) and its elaborate interactions with human society (e.g., through energy use, consumption and production behaviours, transportation, cultural values, institutions and governance). Knowledge from various disciplines in the natural sciences, the social sciences, and arts and humanities needs to be integrated and synthesized to reach a full understanding of the issues behind climate change.

2. Similarly, food security will not be achieved without the development of knowledge in biology and food research to increase food productivity and food varieties. Nor will food security be achieved without advances in the social sciences and economics to understand underlying institutions (e.g., land tenure systems, market related institutions to stabilize food prices) and behaviours (e.g., creating incentives for farmers to increase productivity). Moreover, interdisciplinary research (IDR) combining various research domains including the arts and humanities is essential in addressing ethical issues in research in the Health Sciences. IDR is therefore in high demand for addressing these societal problems.

3. The National Academy of Sciences of the United States of America (USA) summarizes the following four challenges driving IDR in its report "Facilitating Interdisciplinary Research"[1]:
   - ► The inherent complexity of nature and society
   - ► The drive to explore basic research problems at the interfaces
   - ► The need to solve societal problems of disciplines
   - ► The stimulus of generative technologies

   It also regards IDR as having the potential to produce novel and even revolutionary insights.

[1] Available at http://www.nap.edu/catalog/11153/facilitating-interdisciplinary-research.

What is the difference between multidisciplinary, interdisciplinary, and transdisciplinary research?

4. Even though terms such as multidisciplinary research and interdisciplinary research are often used interchangeably, the reviewed IDR literature makes a distinction among these terms.[2]

5. Multidisciplinary research is sometimes viewed as no more or less than the simple sum of parts from multiple disciplines. "Theory, methods, and interpretive standards of the different disciplines are employed. Interpretation of the results from different disciplines typically occurs post hoc, often from the perspective of one discipline that may emerge as dominant within the project."[3]

6. Interdisciplinary research integrates separate disciplinary data, methods, tools, concepts, and theories in order to create a holistic view or common understanding of a complex problem. Beyond that, transdisciplinary research transcends the scope of monodisciplinary worldviews to reach an overarching synthesis. Examples of the results of transdisciplinary research include the concepts of sustainability and feminism.

7. Nissani (1995)[4] in an attempt to develop a working definition of interdisciplinarity, offered the metaphor of mixing fruits. Fruit (apple, mango, orange, etc.) may be served alone (monodisciplinary), in a fruit salad (multidisciplinary), or blended as a smoothie (interdisciplinary). Extending this metaphor to

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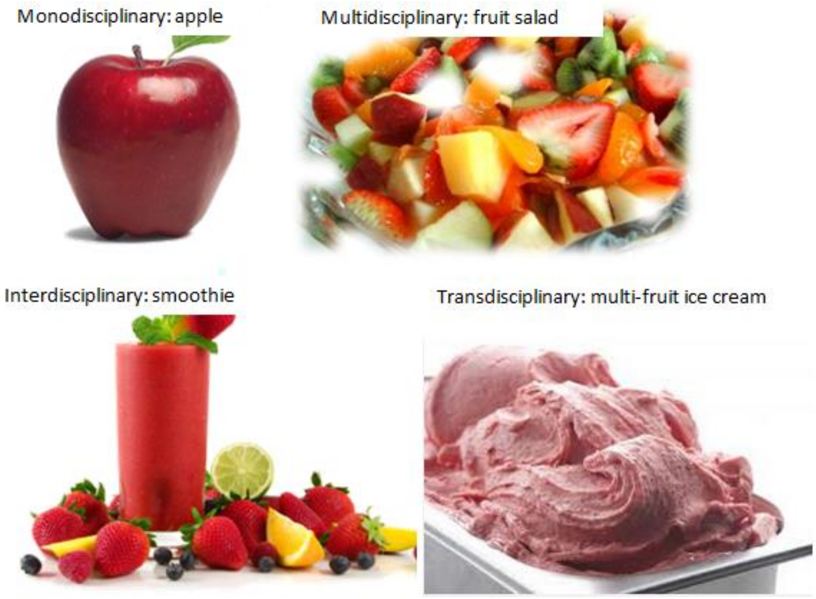
[2] Literature that discusses the differences of these terms include:
- Schummer, J. (2004). Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology. *Scientometrics*, 59(3), 425–465.
- Sonnenwald, D. H. (2007). Scientific collaboration. *Annual Review of Information Science and Technology*, 41(1), 643–681.
- Wagner, C. S., Roessner, J. D., Bobb, K., Klein, J. T., Boyack, K. W., Keyton, J., Boyack, K., Keyton, J., Rafols, I., and Börner, K. (2011). Approaches to understanding and measuring interdisciplinary scientific research (IDR): A review of the literature. *Journal of Informetrics*, 5(1), 14–26.

[3] Rossini, F. A.,and Porter, A. L. (1979). Frameworks for integrating interdisciplinary research. *Research Policy*, 8(1), 70–79.

[4] Nissani, M. (1995). Fruits, salads, and smoothies: A working definition of interdisciplinarity. *Journal of Educational Thought*, 29(2), 121-128.

transdisciplinarity, one might imagine using the smoothie as the basis for a new dessert.[5]



8. The major difference among the three types of cross-disciplinary research is not only the outcome (to what extent knowledge from multiple disciplines is integrated in the resulting research output) but also the cognitive and social processes (e.g., how cross-disciplinary team members interact, how concepts from multiple disciplines are integrated). In practice, quantitatively assessing the processes is difficult and costly. In this report, we measure only the outcome, not the process. We therefore do not make any distinction between the three types of cross-disciplinary research (multi, inter, and trans). In this sense, cross-disciplinary research is arguably the proper term to refer to these three types. However, cross-disciplinary research is a less widespread term compared to interdisciplinary research, especially among policy makers, funders, and the wider audiences. We therefore use the term "interdisciplinary research" throughout the report to refer to all three types of cross-disciplinary research.

Measures of IDR and our approach

9. Both qualitative and quantitative approaches are used to measure IDR. Qualitative measures usually focus on the cognitive and social processes in IDR, trying to detect

[5] Austin, W., Park, C., et al. (2008). "From interdisciplinary to transdisciplinary research: A case study." *Qualitative Health Research* 18(4): 557-564.

integration in the research process, to assess the value of the outcomes of collaborative work and to develop causal inferences about the factors that influence these outcomes. [6] They usually rely on self-assessments by participants using scales of the level of collaboration that occurred. [7]

10. For the quantitative measures, Wagner et al. (2011)[8] reviewed two approaches each consisting of various IDR measures. They call the first and more frequently used approach a "structuralist approach". This approach includes measures of IDR using for example citation analysis, author affiliations, or co-occurrences of keywords from multiple disciplines. Citation analysis makes use of the information contained in article's references or in the articles citing it. The underlying assumption is that interdisciplinary articles are more likely to cite articles from multiple disciplines and are also more likely to be cited by articles from multiple disciplines. Citation analysis is the most frequently used method in measuring IDR. [9] Besides citation analysis, other studies consider whether and to what extent authors of the article are affiliated with faculties from multiple

[6] Drawn from Wagner, C. S., Roessner, J. D., Bobb, K., Klein, J. T., Boyack, K. W., Keyton, J., Boyack, K., Keyton, J., Rafols, I., and Börner, K. (2011). Approaches to understanding and measuring interdisciplinary scientific research (IDR): A review of the literature. *Journal of Informetrics*, 5(1), 14–26.

[7] Examples include:

- Hall, K. L., Stokols, D., Moser, R. P., Taylor, B. K., Thornquist, M. D., Nebeling, L. C., et al. (2008). The collaboration readiness of transdisciplinary research teams and centers. *American Journal of Preventive Medicine*, 35, S161-S172.
- Mâsse, L. C., Moser, R. P., Stokols, D., Taylor, B. K., Marcus, S. E., Morgan, G. D., et al. (2008). Measuring collaboration and transdisciplinary integration in team science. *American Journal of Preventive Medicine*, 35, S151-S160.

[8] Wagner, C. S., Roessner, J. D., Bobb, K., Klein, J. T., Boyack, K. W., Keyton, J., Boyack, K., Keyton, J., Rafols, I., and Börner, K. (2011). Approaches to understanding and measuring interdisciplinary scientific research (IDR): A review of the literature. *Journal of Informetrics*, 5(1), 14–26.

[9] Examples using citation analysis include:

- Adams, J., Jackson, L., and Marshall, S., 2007. Bibliometric analysis of interdisciplinary research. Report to the Higher Education Funding Council for England. Evidence, Leeds.
- Rinia, E. J., van Leeuwen, T. N., and van Raan, A. F. J. (2002). Impact measures of interdisciplinary research in physics. *Scientometrics*, 53, 241-248.

disciplines[10] or whether the article contains vocabulary specific to several disciplines as an indication of IDR.

11. Wagner et al. (2011) called the second approach for IDR measurement "spatial distances". This approach tries to describe the landscape or space within which science operates. For instance, Leydesdorff (2007)[11] has suggested that betweenness centrality can be used as a measure of IDR at the journal level: the more central a journal is in a journal network, the more likely that the journal is interdisciplinary. The "spatial distance" approach is often more suitable as an IDR measure for a set of documents instead of one paper.

12. In this report, we measure IDR at the article level.[12] We therefore adopt the "structuralist approach", specifically citation analysis, as a measure of IDR. Since citations take time to accumulate, the most recent publications (2009-2013) have not been cited often. Results that rely on these small numbers of citations will be less precise.

13. Instead, our approach assigns an IDR score to an article based on its references. Articles that reference other articles that are relatively "far" from each other are considered more interdisciplinary. If an article references other articles that are relatively "close" to each other, this suggests that the original article is situated or categorized within a single discipline.

14. To define how "far" or "close" the references of an article are, we look at the journals in which they are published. If these journals are "far" from each other, these references are also "far" from each other. If the journals are "close", we class the references as being "close".

15. How, then, do we define whether two journals are "far" from or "close" to one another? We count the frequency in which two

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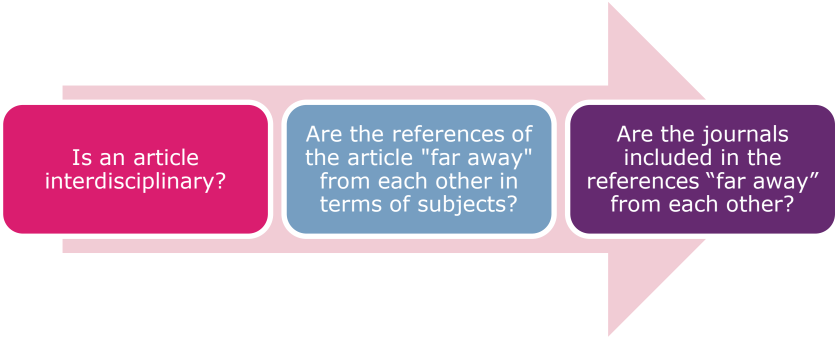
[10] See Porter, A. L., Roessner, D. J., and Heberger, A. E. (2008). How interdisciplinary is a given body of research? *Research Evaluation*, 17, 273–282 and Schummer, J. (2004). Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology. *Scientometrics*, 59, 425–465.

[11] Leydesdorff, L. (2007a). Betweenness centrality as an indicator of the interdisciplinarity of scientific journals. *Journal of the American Society for Information Science and Technology*, 58, 1303–1319.

[12] The measures are then aggregated at the country level to provide results on international comparison of the absolute number of IDR and are also aggregated for each year to show the trend of development of IDR.

journals are co-cited in the references of all Scopus publications for a certain period. The more often those journals occur together, the more likely that they are close to each other. The figure below summarizes the logic behind our method, and a detailed description of the method is included in Appendix A.



16. There are two major advantages of our method. Firstly, the notion of "far" or "close" is independent of any pre-defined subject classification, and purely determined by how often the journals co-occur in article references. One problem with using journal classification is that journal classification schemes require stability and therefore do not always reflect new development in areas of research. Similarly, the rigidness of such a classification system does not allow for quantifying subtle versus large differences between disciplines. A publication from one relatively small discipline that cites another publication in the nearest adjacent discipline would be categorized as interdisciplinary. However, if a publication in a larger discipline cites a publication that is still within the larger discipline but on a largely unrelated topic it would not be categorized as interdisciplinary.

17. Secondly, our approach captures the dynamics of the research landscape. Subject areas are constantly emerging and changing. What is considered IDR today may be monodisciplinary tomorrow. Our approach accommodates this phenomenon. Since we measure how "far" or "close" the journals are based on co-citations, our measure of the distance between journals changes when we apply the method to different document sets. For instance, if subjects A and B merge into a single discipline during the period 2009-2013, 2009 co-occurrence data would imply that journals from subject A and B are further from each other than 2013 data.[13]

[13] We have tested this hypothesis (see Appendix A for details) and conclude that five years (2009-2013) is too short a period for the research landscape to see dramatic changes. In order to achieve more

Limitations of the methodology

18. A body of literature is available on the limitations and caveats in the use of 'bibliometric' data, such as the accumulation of citations over time, the skewed distribution of citations across articles, differences in publication and citation practices between fields of research, and applicability to Social Sciences and Humanities research[14]. More broadly, Wilsdon, J., et al. (2015)[15] provides a review of using metrics in assessing the quality and broader impact of scientific and scholarly research. They also raised a few concerns regarding the use of metrics and proposed the notion of using "responsible metrics" in research assessment.

19. In the Social Sciences and the Humanities, the bibliometric indicators presented in this report for these research domains must be interpreted with caution because a reasonable proportion of research outputs in such research domains take the form of books, monographs and non-textual media. Despite the continuous efforts in increasing the coverage (in particular for books) in Scopus, some of these document types are not covered by Scopus[16]. As such, analyses of journal articles, reviews and conference proceedings, their usage and citation, provides a less comprehensive view in these research domains than in others, where these three types of documents comprise the vast majority of research outputs.

20. Related to this point and more specific to our methodology in defining IDR, our approach is a citation-based approach. This implies that the results from the analysis are more robust for some research domains than for others. In order for a publication to obtain a score using our method, this publication

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robustness in our results, we have used the full five year data (2009-2013) to calculate the distances of journals.

[14] To distinguish the research domain Arts & Humanities from the Scopus subject area Arts & Humanities, in this report we use "the Humanities" when referring to the research domain Arts & Humanities which includes the divisions listed in Appendix C.

[15] Wilsdon, J., et al. (2015). The Metric Tide: Report of the Independent Review of the Role of Metrics in Research Assessment and Management. DOI: 10.13140/RG.2.1.4929.1363

[16] See Scopus Content Coverage Guide at http://www.elsevier.com/_data/assets/pdf_file/0007/69451/sc_content-coverage-guide_july-2014.pdf for the list of document types covered in Scopus.

must have sufficient number of references that are covered by Scopus. In the Humanities, a relatively large percentage of publications either do not contain references in the form of a bibliography or do not contain enough references covered by the Scopus database. As an abstract database, Scopus does not include the full text of publications and therefore does not cover references in the form of footnotes.

21. We are able to obtain an IDR score for 8.7 million publications out of in total 11.2 million publications covered by Scopus in the period 2009-2013. This implies that 78% of the Scopus publications in this period are used in this report. The percentage differs from field to field and from country to country. We provide detailed percentages in Appendix A. In general our method can tell how interdisciplinary an article is for the great majority of publications in the research domains Natural Sciences, Engineering& Technology, Health Sciences, and (to a slightly lesser extent) Social Sciences. For the Humanities, the percentages are lower. This may limit the ability of the approach to give a comprehensive view of IDR in the Humanities, and the results on the Humanities in this report require cautious interpretation.

22. Since most publications get an IDR score with our method, we are able to sort the publications by their IDR scores and examine the world's top 10% most interdisciplinary publications for the period 2009-2013.[17] Throughout the report, this set of publications is compared to all publications with an IDR score to investigate whether IDR is associated with high citation impact, high usage, and high levels of collaboration.

[17] The IDR score is a continuous variable between -1 and 1. Publications with the lowest scores usually involve IDR across research domains (e.g., natural sciences with social sciences). When the score increases, we encounter the publications with collaborations within the research domains. The ones with the highest scores are the monodisciplinary publications.

Scopus (www.scopus.com)

Scopus is Elsevier's abstract and citation database of peer-reviewed literature, covering 55 million documents published in over 21,000 journals, book series and conference proceedings by some 5,000 publishers. Scopus coverage is inclusive across all major research fields, with 7,400 titles in the Physical Sciences, 6,700 in the Health Sciences, 4,400 in the Life Sciences, and 7,600 in the Social Sciences (the latter including 4,200 Arts & Humanities related titles).

Titles which are covered are predominantly serial publications (journals, trade journals, book series and conference material), but considerable numbers of conference papers are also covered from stand-alone proceedings volumes (a major dissemination mechanism, particularly in the Computer Sciences). Acknowledging that a great deal of important literature in all research domains (but especially in the Social Sciences and the Arts & Humanities) is published in books, Scopus has begun to increase book coverage in 2013, aiming to cover 75,000 books by 2015.

The Arts and Humanities

As of 2008, Scopus covered around 2,000 humanities titles. In 2009, to increase the number of humanities titles in the database, project MUSE (a not-for-profit full-text platform of many Humanities journals with international relevance from primarily US-based university presses) and the initial European Reference Index for the Humanities list were used to identify additional relevant titles. In 2011, a similar project was executed in which the coverage of the revised European Reference Index for the Humanities list, the Social Science Citation Index, the Arts & Humanities Citation Index, the titles list of Evaluation Agency for Research and Evaluation, France, and the humanities journal indexes Cairns and Francis were used. These journals were reviewed and added, together with the humanities titles selected for Scopus coverage via the Scopus Title Evaluation Process.

Scopus coverage has now grown to almost 3,500 humanities titles (4,200 when including humanities-related titles) and includes all serial publication types, such as journals, book series and conference series. The majority of Humanities titles (80%) go back to 2002 while 15% of titles go back as far as 1996 and 5% of titles do not have any back coverage. There are plans to extend the coverage of additional journals back to 1996.

Subject classification

23. The Australian and New Zealand Standard Research Classification (ANZSRC)[18] is used for subject classification throughout the report. Scopus All Science Journal Classification[19] was mapped to ANZSRC groups. More specifically, we mapped the Scopus detailed subject classification (334 subjects) to 157 ANZSRC groups. Appendix B lists the exact mapping. We report at the level of 22 ANZSRC divisions. With the hierarchy structure of the ANZSRC, each division consists of multiple groups. Therefore, each division is an aggregation of publications that belong to the groups under this division.[20]

24. With this mapping:
   - ► All Scopus subjects are matched to at least one ANZSRC group except the subject Multidisciplinary, which includes journals such as Nature and Science. This subject does not have a match in ANZSRC. The publications belonging to Multidisciplinary in Scopus are included when we report indicators for "All divisions" but they will not influence any individual division.
   - ► Out of the 157 ANZSRC groups, 137 are matched to at least one Scopus subject. This means that 20 ANZSRC groups are not matched. They are at a more detailed level than the Scopus detailed subjects. These 20 groups are listed in Appendix B.
   - ► Each publication is assigned to one or multiple divisions depending on the journal in which it is published.

For consistency, throughout the report we refer to the components of ANZSRC as "divisions" or "groups", and refer to the components of Scopus All Science Journal Classification as "subjects" or "subject areas". We also sometimes refer to a group of ANZSRC divisions as a "research domain". The mapping between ANZSRC divisions and the research domains used in the report is presented in Appendix C.

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[18] http://www.arc.gov.au/era/anzsrc.htm

[19] The list of Scopus subject areas can be found in the title of Scopus at http://www.elsevier.com/_data/assets/excel_doc/0015/91122/title_list.xlsx.

[20] One publication may belong to multiple groups within one division. When aggregating to the division level, duplicated publications are removed.

Chapter 1
IDR Output

This chapter summarizes the findings on IDR output. It compares the IDR output of the UK to comparator countries in both absolute and relative terms. It also uses a relative IDR index to detect divisions in which there is a high level of IDR activity for each country. Additionally, it analyses to what extent IDR publications are contributed by academia.

1.1 Key findings

PERCENTAGE OF THE UK'S PUBLICATIONS THAT BELONG TO TOP 10% IDR

9.1%

In 2013 around 9.1% of the UK's publications with an IDR score belong to world top 10% IDR. China leads on this indicator (12.3%).

ACADEMIA'S CONTRIBUTION TO IDR

85%

In 2013 around 85% of the UK's publications that belong to the world's top 10% IDR have at least one author from academia.

COUNTRIES THAT LEAD IN THE PERCENTAGE OF PUBLICATIONS THAT BELONG TO THE TOP 10% IDR

China and Brazil

In 2013, 12.3% of publications authored by Chinese researchers with an IDR score belong to the world's top 10% IDR. This is followed by Brazil with 11.0%.

1.2 Emerging countries are leading by share of interdisciplinary research out of total output

25. The research landscape of the world has changed dramatically in the past years with emerging countries[21] such as China and Brazil greatly increasing their research output in absolute and relative terms. Take China for example: its research output increased from 310,353 papers in 2009 to 444,744 papers in 2013, contributing to around 20% of world publications. This trend is also reflected in Figure 1.1 which presents the number of publications that belong to the world's top 10% IDR. In 2013, China catches up with the USA with 45,051 top 10% IDR publications. UK researchers authored 12,210 top 10% IDR publications in 2013, which is an increase from 8,757 in 2009. Histograms that present the number of publications in different ranges of IDR scores for the UK and the world can be found in Figure A.1 and A.2 in Appendix A.

How are publications counted?
We count the following types of documents as publications: articles, reviews, and conference proceedings.

Full counting is used. For example, if a paper has been co-authored by one author from the UK and one author from the USA, the paper counts towards both the publication count of the UK and the publication count of the USA. Total counts for each country are the unique count of publications.

[21] Countries that have increased their research output rapidly in recent years.

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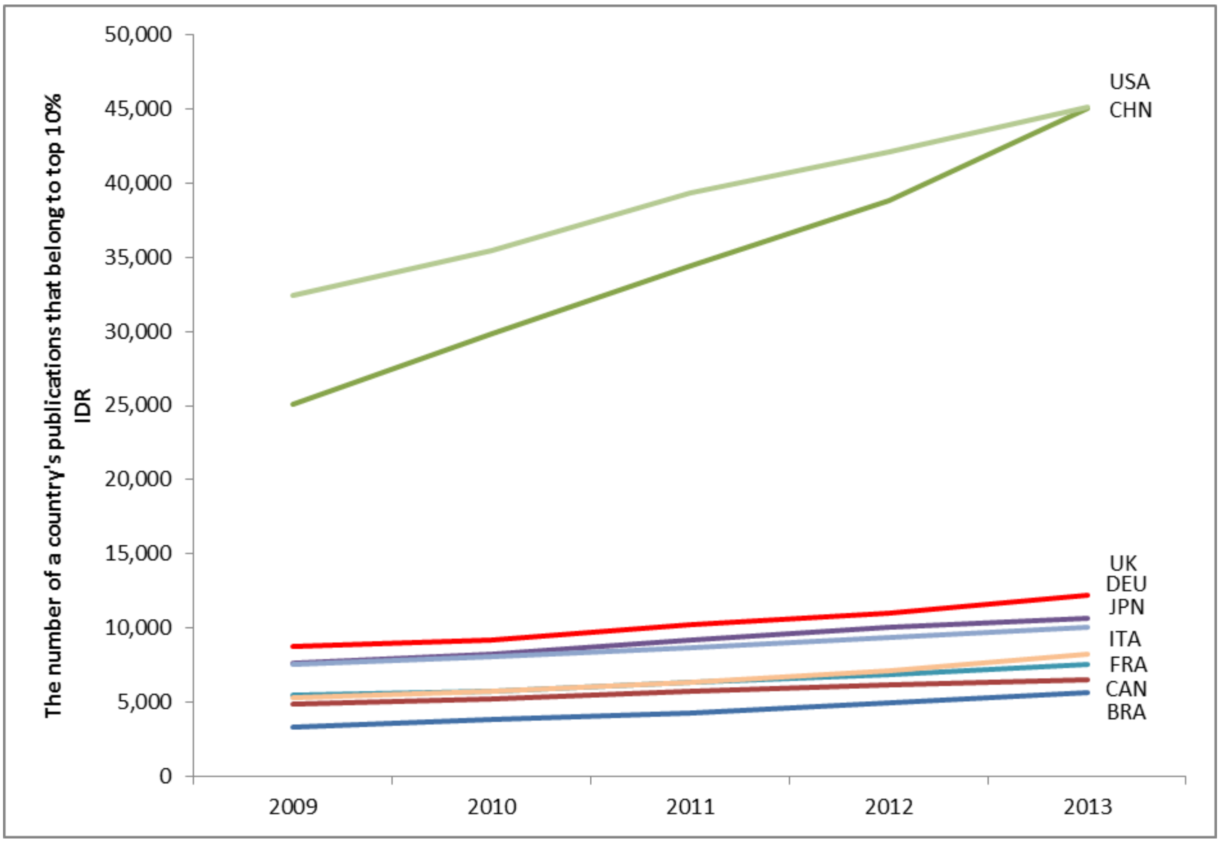
Figure 1.1— *The number of publications that belong to the top 10% IDR; all divisions; per country; per year in the period of 2009-2013.*



26. It is natural that the number of publications in the top 10% IDR is highly correlated with the country's total publications: countries with a larger number of publications are also more likely to have a larger number of publications in the top 10% IDR. Therefore, the absolute numbers do not tell how intensively a country focuses its research activities on IDR. Figure 1.2 takes this into consideration by normalizing the absolute numbers of publications in the top 10% IDR by the total number of publications (with an IDR score) of the country. Strikingly in this figure, emerging countries (China and Brazil) are leading. For all years in the period of 2009-2013, China has the highest percentage of publications that belong to the top 10% IDR. In 2013, 12.3% of publications authored by Chinese researchers belong to the world's top 10% IDR. This number is followed by Brazil's 11.0% and Italy's 10.3%. The USA and Japan have very similar percentages in 2013 (9.7%), followed by the UK's 9.1%. Germany, Canada, and France have the lowest percentages.

27. Even though little information can be found in the literature on which countries are more intensively involved in IDR, the more mature countries in research (e.g., the USA and the UK) often perform better than emerging countries in indicators such as citation impact, collaboration, and usage by wider research community and by industry. The picture changes when we look at IDR: China and Brazil clearly hold the leading positions.

28. We have tested various hypotheses that may explain this finding. First, is this finding caused by the relatively low percentage of China's publications that have an IDR score (Figure A.5)? To test this hypothesis, we reproduced Figure 1.2 but restricted the document set to the division Biological Sciences in which the percentage of publications that have an IDR score is higher than 90% for all countries. China still has the highest share of the top 10% IDR, followed by Italy and Brazil. This hypothesis at least cannot fully explain the finding.

29. Second, is this because China's publications concentrate more on divisions that have a higher share of top 10% IDR publications? Again we reproduced Figure 1.2 but for a number of divisions, Biological Sciences and Technology, with a high share of top 10% IDR publications, and Economics with a low share. In all three divisions, China remains at the leading position. Brazil takes either the second or the third position. Again this hypothesis cannot fully explain the finding.

30. Third, is this because China has a high portion of publications that only have a small number references? The fewer the number of references, the less the information the IDR score is based on and therefore the less reliable the IDR score is. China and Brazil both have a high share of non-English publications in local journals so it is possible that these publications are not covered by Scopus. We did a simple test by comparing Figure 1.2 produced with and without publications with only two references covered by Scopus. The two charts are similar, implying that the small number of references is not the main cause.

31. To probe the reasons behind this result, we take a closer look at the development of interdisciplinary research in the UK and China in Box 1. We see many similarities. Both the UK's research councils and China's science foundations are supporting IDR. Many interdisciplinary research centres have been set up in top universities in both countries, providing the

organizational support needed for IDR. For China, the recognition of the importance of IDR to innovations and breakthroughs in research seems to be at a higher level: to quote China's "National Guideline on Medium- and Long-Term Programme for Science and Technology Development 2006-2020" issued by the State Council of China, "Interactions across research fields in basic sciences, between basic and applied sciences, between science and technology, and the integration cross natural sciences, arts, humanities and social sciences, often result in major research discoveries and emerging disciplines. It is one of the most active parts of scientific research. We need to give high attention to it in our research management".

32. Another plausible reason for China's high percentage of top 10% IDR is that the establishment of its discipline-based faculty system is relatively new compared with the countries that are more mature in research. From Soviet Union style university and faculty systems in the 1950s to more European/American style faculty systems nowadays, Chinese universities and colleges have experienced many big changes in their organizations. Many universities merged and, within universities, many faculties reorganized. This may have led to a higher level of cross-faculty researcher mobility and collaboration compared to countries such as the USA or the UK where the faculty systems have been established for more than 100 years.

33. Our publications and citation data are not sufficient to test these two plausible reasons (the recognition of IDR at a higher level in China and China's relative newer faculty system). More qualitative research is needed to verify these reasons.

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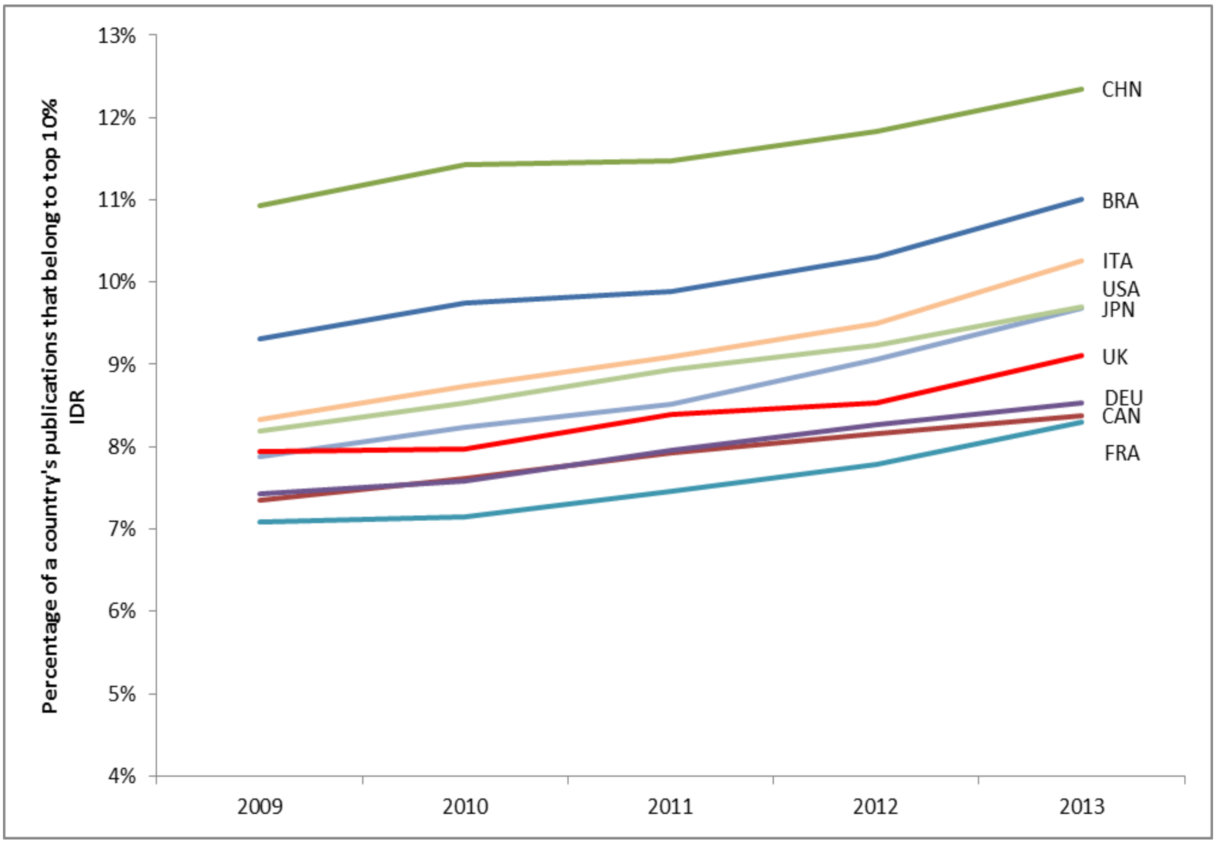
Figure 1.2— *Percentage of publications with an IDR score that belong to the top 10% IDR; all divisions; per country; per year from 2009-2013.*



Box 1: Interdisciplinary Research in the UK and China

Many interdisciplinary research centres have been established in the UK. They include for example the Interdisciplinary Research Centre in Materials Processing in the University of Birmingham, the Cambridge Interdisciplinary Research Centre on Ageing, the Centre for Humanities Interdisciplinary Research Projects at University College London, the Centre for AIDS Interdisciplinary Research and the School of Interdisciplinary Area Studies at Oxford.

The UK's research councils support excellent interdisciplinary research through co-funding agreements between research councils and have run specific interdisciplinary funding programmes within their research. In addition various research councils are also involved in cross-council funding programmes addressing global challenges which require an interdisciplinary approach (http://www.rcuk.ac.uk/research/xrcprogrammes/).

Since the start of the 21st century, national government and funding bodies in China have put intensive effort into stimulating IDR. For example, the National Natural Science Foundation of China has included interdisciplinary research in its major research plans. Moreover, the importance of IDR is also recognized in China's "National Guideline on Medium- and Long-Term Programme for Science and Technology Development 2006-2020" issued by the State Council of China.

In this context, interdisciplinary research facilities are emerging. To name a few, Shandong University founded the Laboratory for Health Economics and Policy, and the Environmental Archaeology Laboratory; the Chinese Academy of Sciences established the Shanghai Interdisciplinary Research Centre of Biology and Chemistry; Peking University set up the Academy for Advanced Interdisciplinary Studies. Zhejiang University established the Interdisciplinary Social Science Research Centre and Tsinghua University has the interdisciplinary AIDS Research Centre.

The discussion of China is drawn from National Planning Office of Philosophy and Social Science China. 2011. Feasibility Analysis of Interdisciplinary Research Report Series, No. 6. Available at http://www.npopss-cn.gov.cn/GB/220182/227704/15319114.html (in Chinese).

34. The percentages of research output that belong to IDR differ not only across countries but also across divisions. Figure 1.3 shows that, in general, divisions in the Natural Sciences and Engineering & Technology domains have higher percentages of publications in the top 10% IDR. In 2013, Technology has the highest percentage among all divisions at 15.7%. This is likely because Technology is a highly applied division which is naturally linked to other divisions related to agriculture, engineering, and biology. Divisions in the research domains

Social Sciences and the Humanities in general have lower percentages. Economics has the lowest percentage in 2013 (3.2%).

35. For all divisions except Law & Legal Studies and a further three divisions in the Humanities domain, the percentages of publications in top 10% IDR increased from 2009 to 2013. For most of the divisions, the increase is significant at the 5% level using the Binomial Proportion Test, which implies that IDR is a growing trend in the research landscape in most of the divisions.[22] We should however note that the coverage of Scopus publications using our method is lower in the Humanities than in other research domains, and that the results therefore need to be treated with caution.

36. The pattern is similar if we only look at the UK (Figure 1.4). The Information & Computing Sciences leads this percentage (14.8%) in 2013, likely because of its wide application to other divisions. This reason may also apply to the Mathematical Sciences in which mathematical models are frequently illustrated by applying them to topics in other divisions (e.g., Computer Sciences, Economics). For the UK, Technology, the Chemical Sciences, Engineering, and the Medical & Health Sciences also have a percentage above 10% in 2013. Similar to the world, for most of the divisions in the Natural Sciences, Engineering & Technology, and Social Sciences[23], the percentage increased from 2009 to 2013, implying growing research activities in IDR in the UK in these research areas. For divisions in the research domains of the Humanities, there is either a decrease or an insignificant increase from 2009 to 2013.

---

[22] One may argue that this trend is maybe influenced by the fact that Scopus coverage changes from year to year. Since there is no good reason to believe that the newly included publications in Scopus are more likely to be interdisciplinary, it is unlikely that the expansion of Scopus is the major factor that contributed to this growing trend.

[23] The increase is not significant for some of the Social Science divisions.

+

Figure 1.3— *Percentage of publications with an IDR score that belong to the top 10% IDR; per division; for the world; 2009-2013. Error bars show the Wald 95% confidence intervals and stars indicate a significant change (at the 5% significance level) from 2009 to 2013 using the Binomial Proportion Test.*

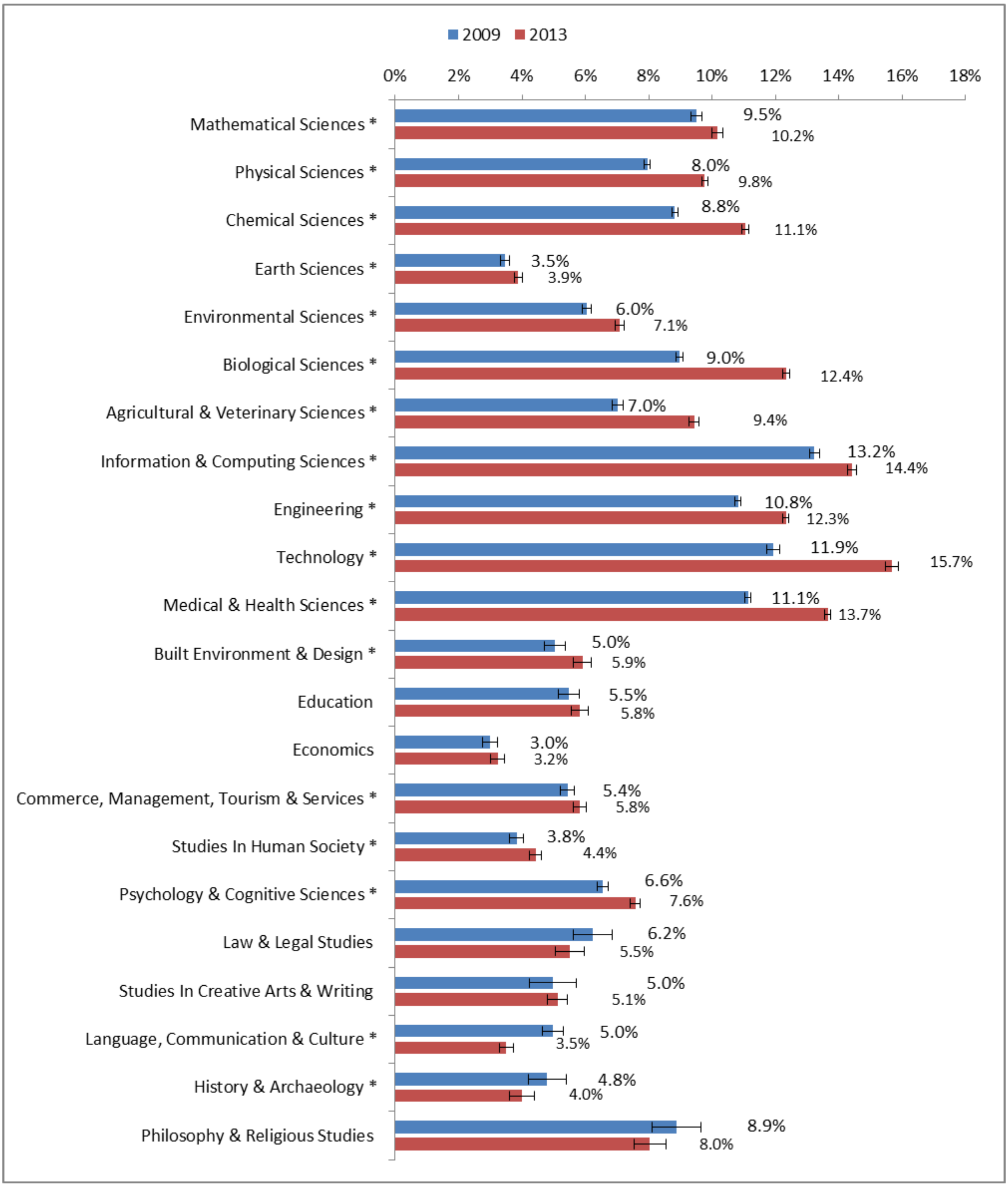


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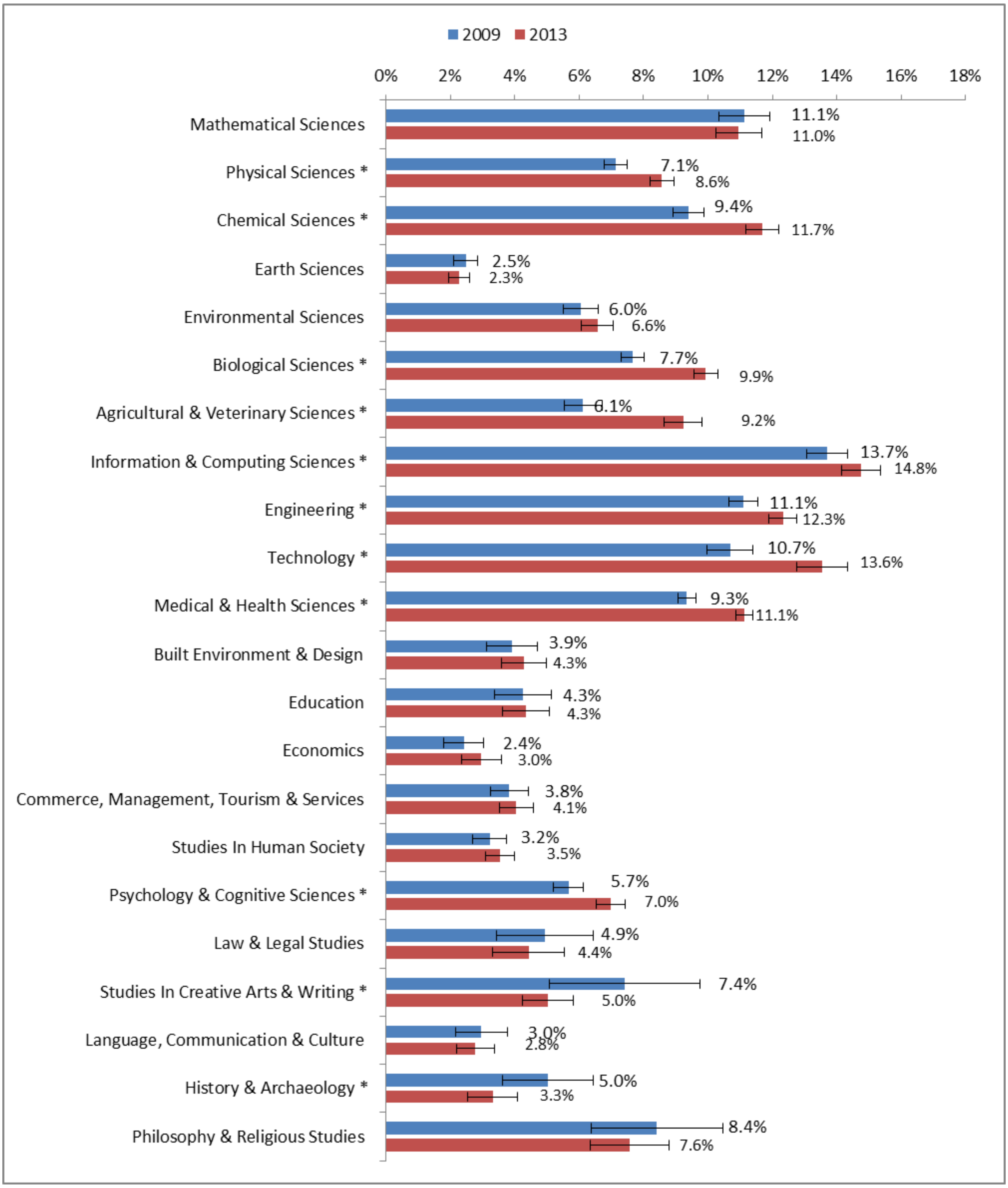
Figure 1.4— *Percentage of publications with an IDR score that belong to the top 10% IDR; per division; for the UK; for 2009 and 2013. Error bars show the Wald 95% confidence intervals and stars indicate a significant change (at the 5% significance level) from 2009 to 2013 using the Binomial Proportion Test.*



1.3 UK IDR is highly focused on divisions in the Social Sciences and the Humanities

37. We see in the previous section that divisions in the Natural Sciences usually have a higher percentage of publications that belong to IDR. This applies to the world, the UK, and all comparator countries. If a country has a high percentage of IDR research in Technology, does that imply that the country's IDR focuses on Technology compared to the world and other countries? This is not necessarily true, because other countries also have a high percentage of IDR in Technology.

> What is the relative IDR index?
> The relative IDR index is defined as a country's share of its top 10% IDR publications across division relative to the global share of top 10% IDR publications in the same division.
>
> To illustrate this calculation, the UK publishes 3,655 top 10% IDR papers in Mathematical Sciences in the period of 2009-2013, and 51,356 papers with an IDR score. The world publishes 54,077 top 10% IDR papers in Mathematical Sciences in the period 2009-2013, and 872,181 papers with an IDR score. Therefore, the relative IDR index for the UK in Mathematical Sciences is (3655/51356)/(54077/872181)=1.15.

38. To correct for this, we normalize the country's percentage of publications in top 10% IDR in a certain division by that of the world. We call this indicator the relative IDR index. If the index is greater than 1, it implies that the country has a higher level of IDR activities in this division compared to the world average. The index is equal to 1 for the world.

39. Figure 1.5 and Figure 1.6 show the relative IDR index for each division for the UK and comparator countries. According to the patterns the countries exhibit, they can be categorized into three groups.

40. The UK, Canada, and the USA belong to the first group. They all have much higher IDR activities in the divisions in the research domains Social Sciences and the Humanities. This is most obvious for the UK where the relative IDR index reaches as high as 3 while the numbers are mostly below 2 for other countries. This implies that even though divisions in the Humanities domain and the Social Sciences in general have a lower share of top 10% IDR publications out of all publications in these divisions, the UK's research in the Humanities and the Social Sciences contributes a much higher portion of top 10% IDR publications compared to other comparator countries. We need however to be careful with the high relative IDR index of the divisions in the Humanities. Since the number of top 10% IDR publications is in general low for these divisions, the relative IDR index is less precise for these divisions.

41. The second group of countries shows the opposite. They have relatively low IDR activities in divisions belonging to research domains the Social Sciences and Humanities. Instead their IDR activities are more intensive in the Natural Sciences. This group includes Brazil, China, and Japan. For Brazil and China, the leading positions we have observed in the previous section are largely contributed by their intensive IDR activities in the Natural Sciences.

42. The last group includes Germany, France, and Italy. They have a more balanced distribution of IDR activities across divisions. For most of the divisions, the index is close to the world average of 1.

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Figure 1.5— *Relative IDR index; per division; for the UK; for 2009-2013.*

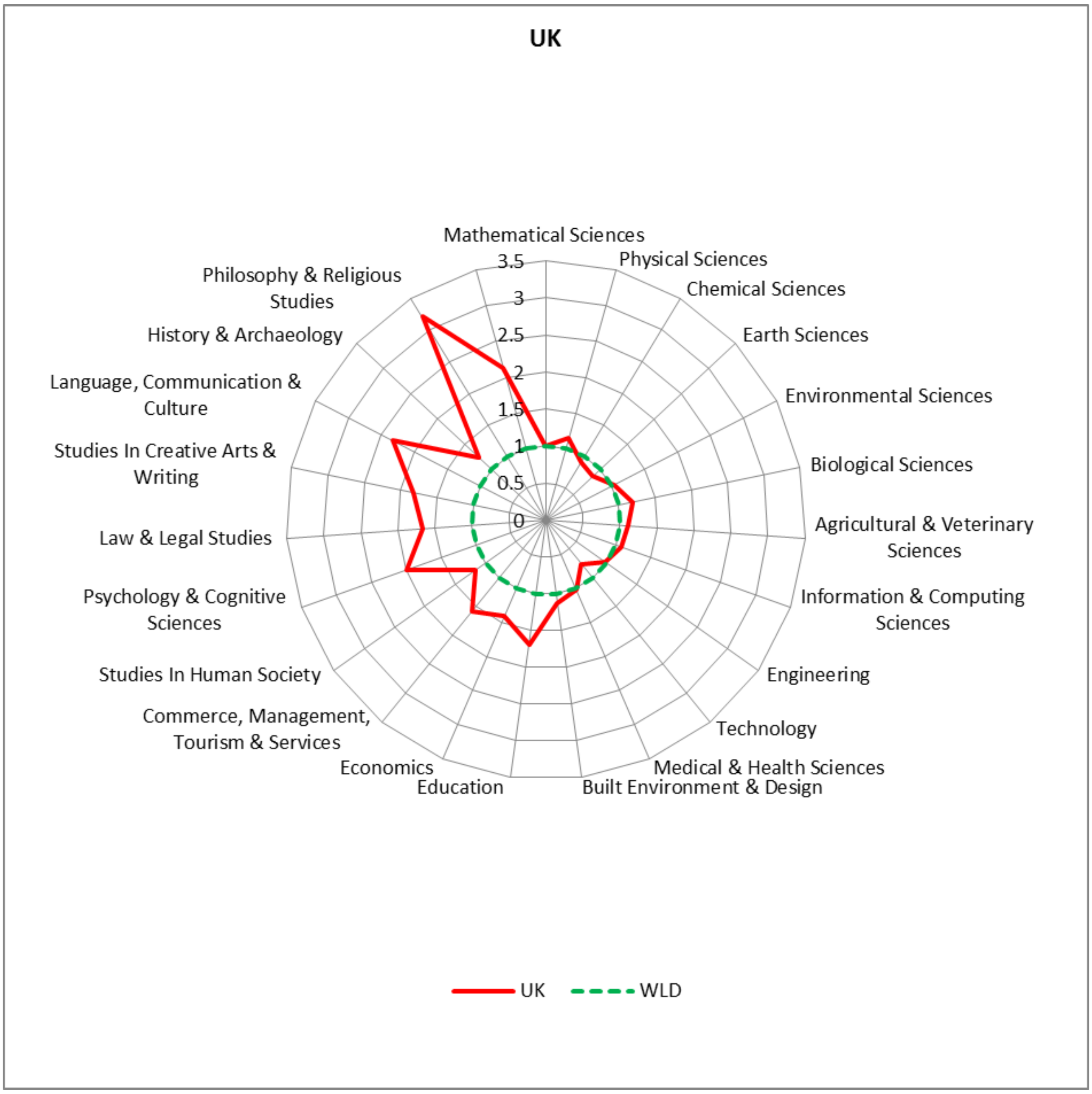

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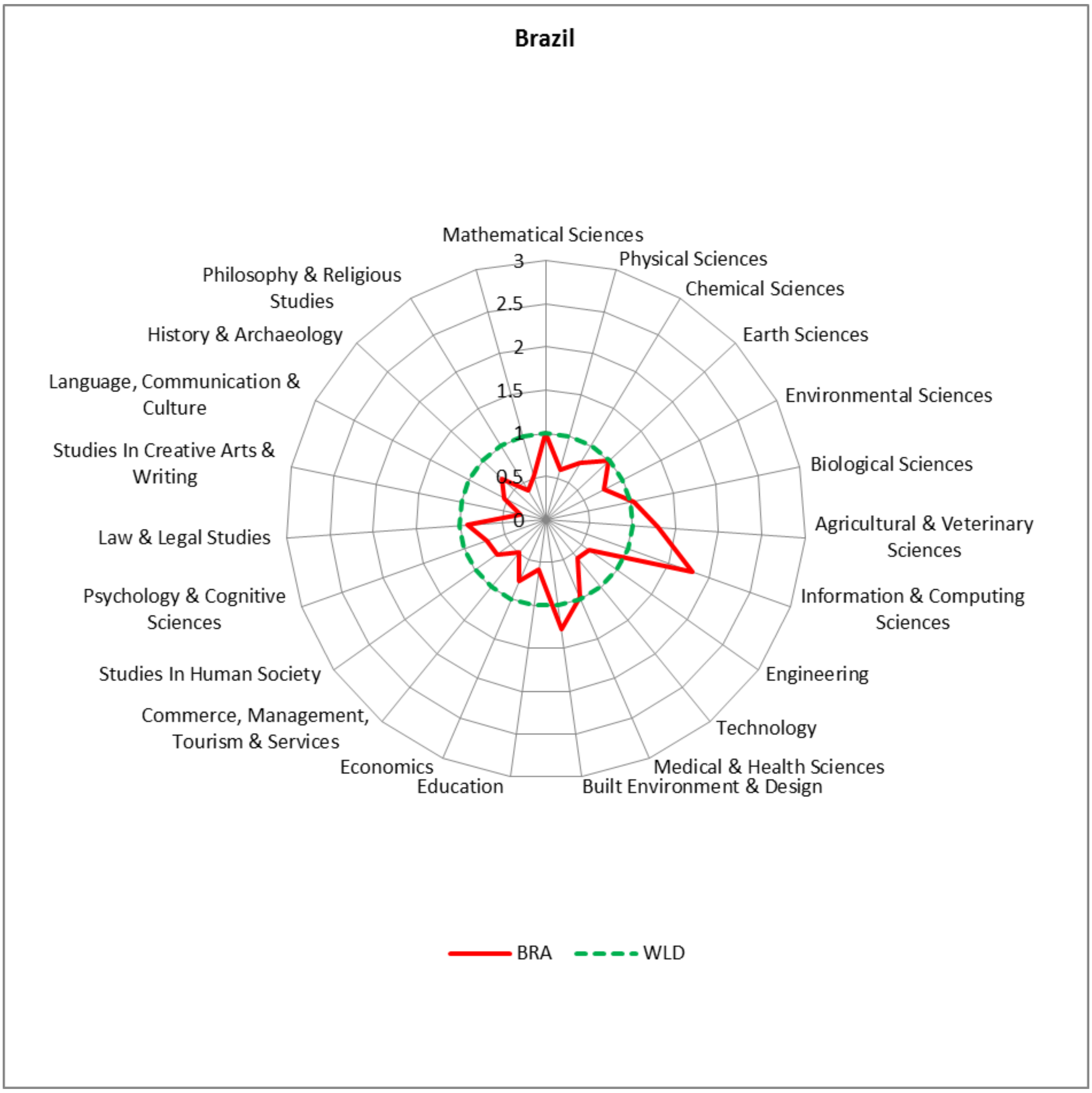
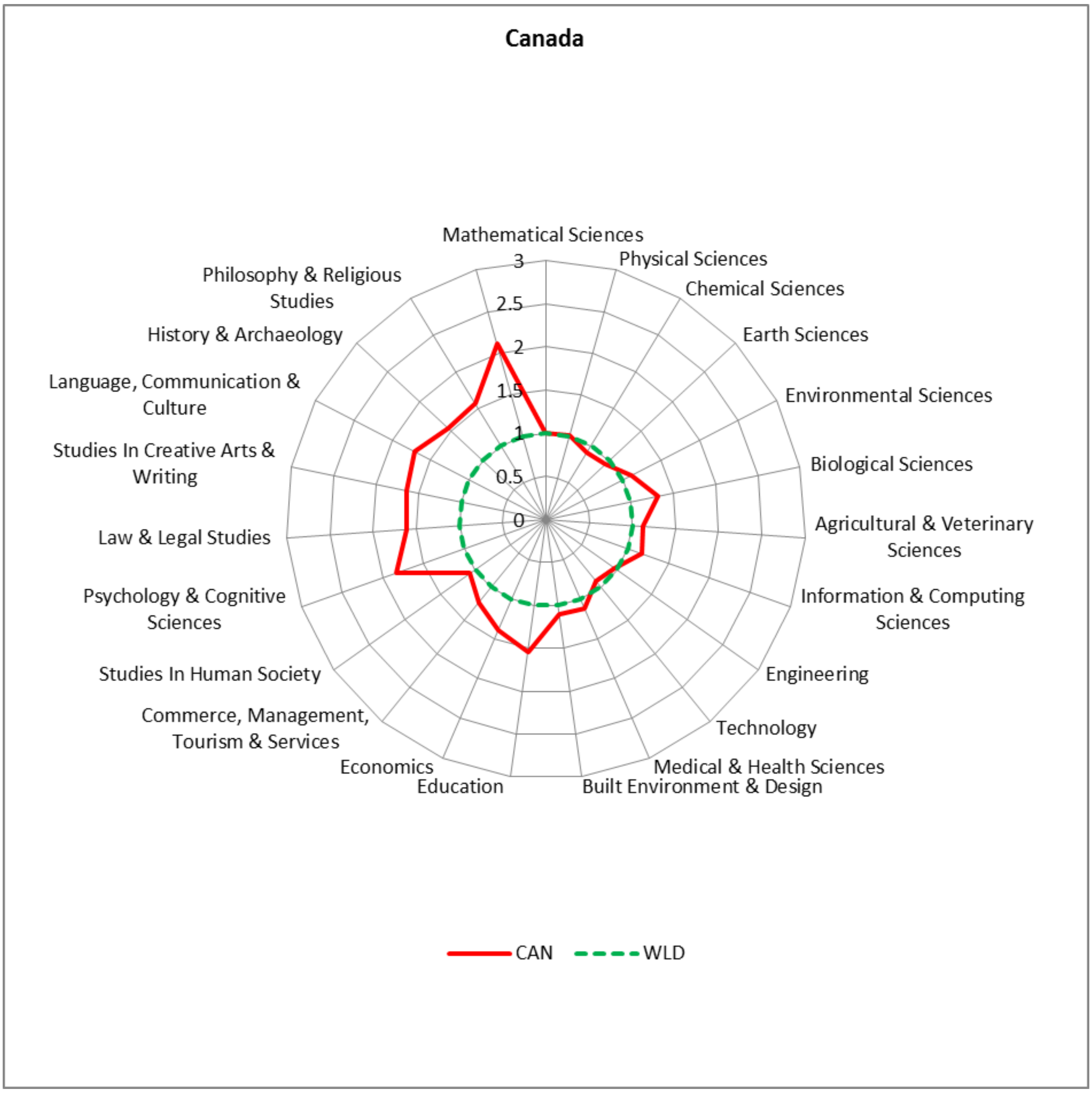
Figure 1.6— *Relative IDR index; per division; per country; for 2009-2013.*

a. Brazil



b. Canada


Canada
Mathematical Sciences
Physical Sciences
Chemical Sciences
Earth Sciences
Environmental Sciences
Biological Sciences
Agricultural & Veterinary Sciences
Information & Computing Sciences
Engineering
Technology
Medical & Health Sciences
Built Environment & Design
Education
Economics
Commerce, Management, Tourism & Services
Studies In Human Society
Psychology & Cognitive Sciences
Law & Legal Studies
Studies In Creative Arts & Writing
Language, Communication & Culture
History & Archaeology
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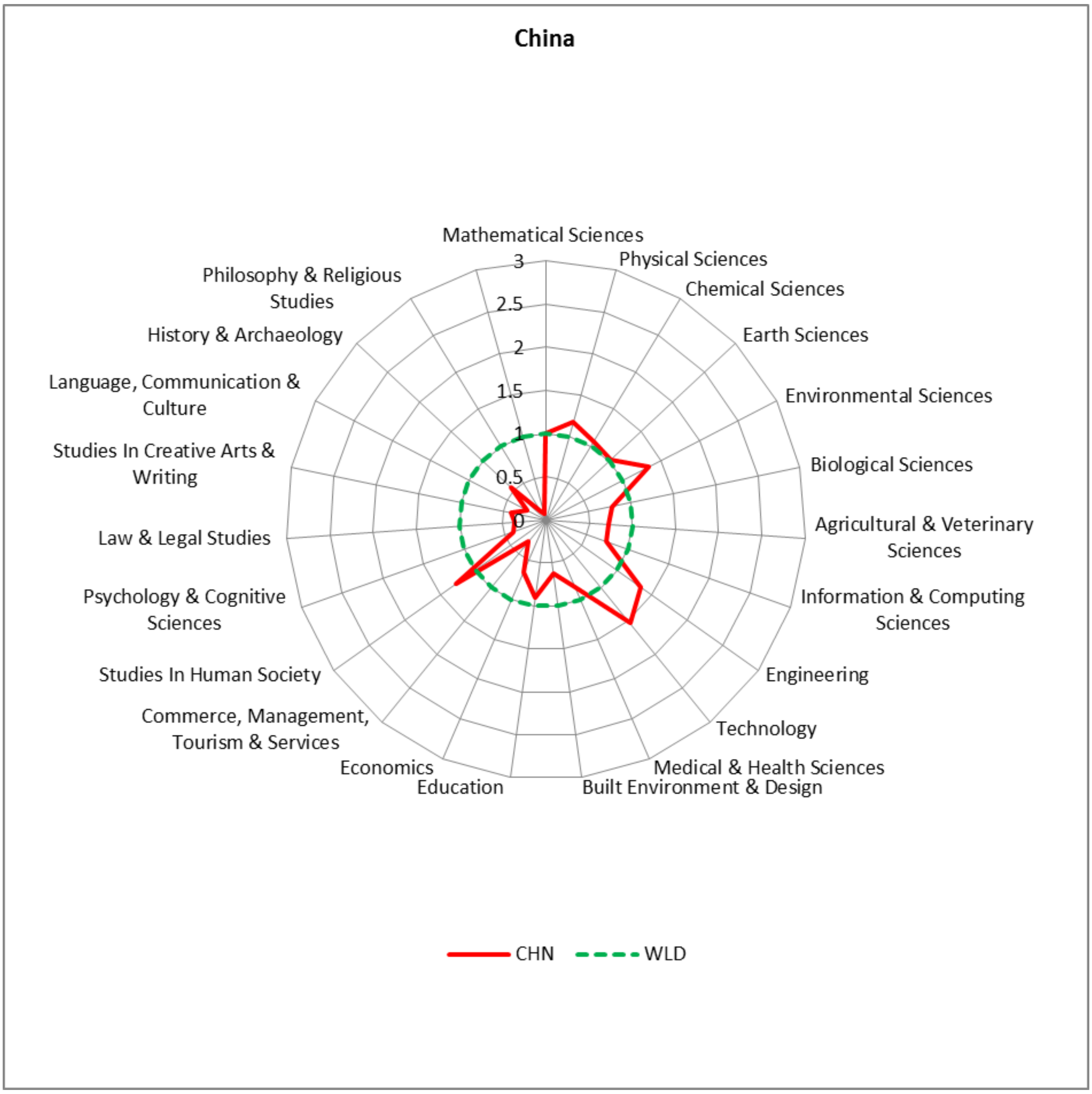
c. China


China
Mathematical Sciences
Physical Sciences
Chemical Sciences
Earth Sciences
Environmental Sciences
Biological Sciences
Agricultural & Veterinary Sciences
Information & Computing Sciences
Engineering
Technology
Medical & Health Sciences
Built Environment & Design
Education
Economics
Commerce, Management, Tourism & Services
Studies In Human Society
Psychology & Cognitive Sciences
Law & Legal Studies
Studies In Creative Arts & Writing
Language, Communication & Culture
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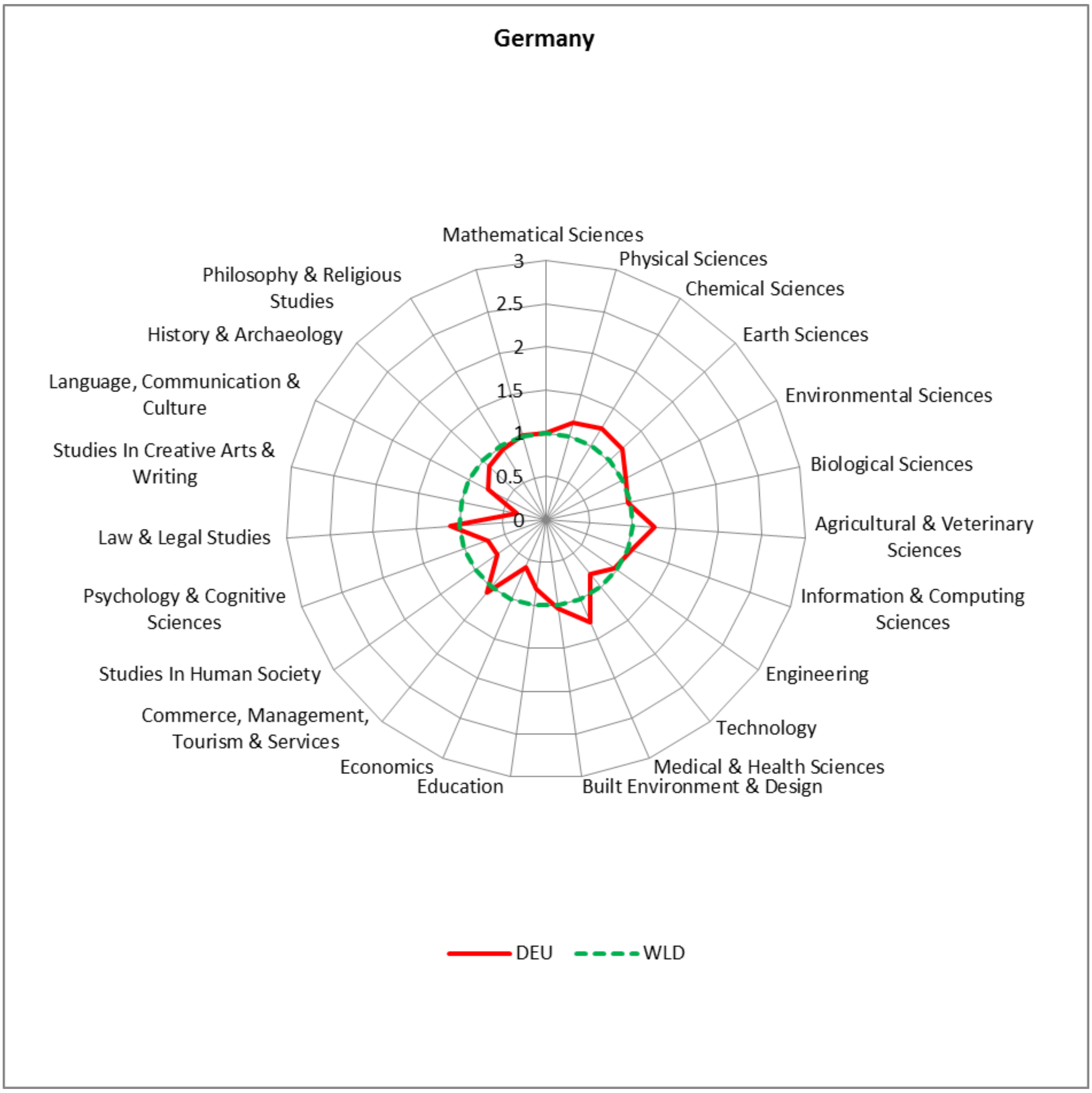
d. Germany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Chemical Sciences
Earth Sciences
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Information & Computing Sciences
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Built Environment & Design
Education
Economics
Commerce, Management, Tourism & Services
Studies In Human Society
Psychology & Cognitive Sciences
Law & Legal Studies
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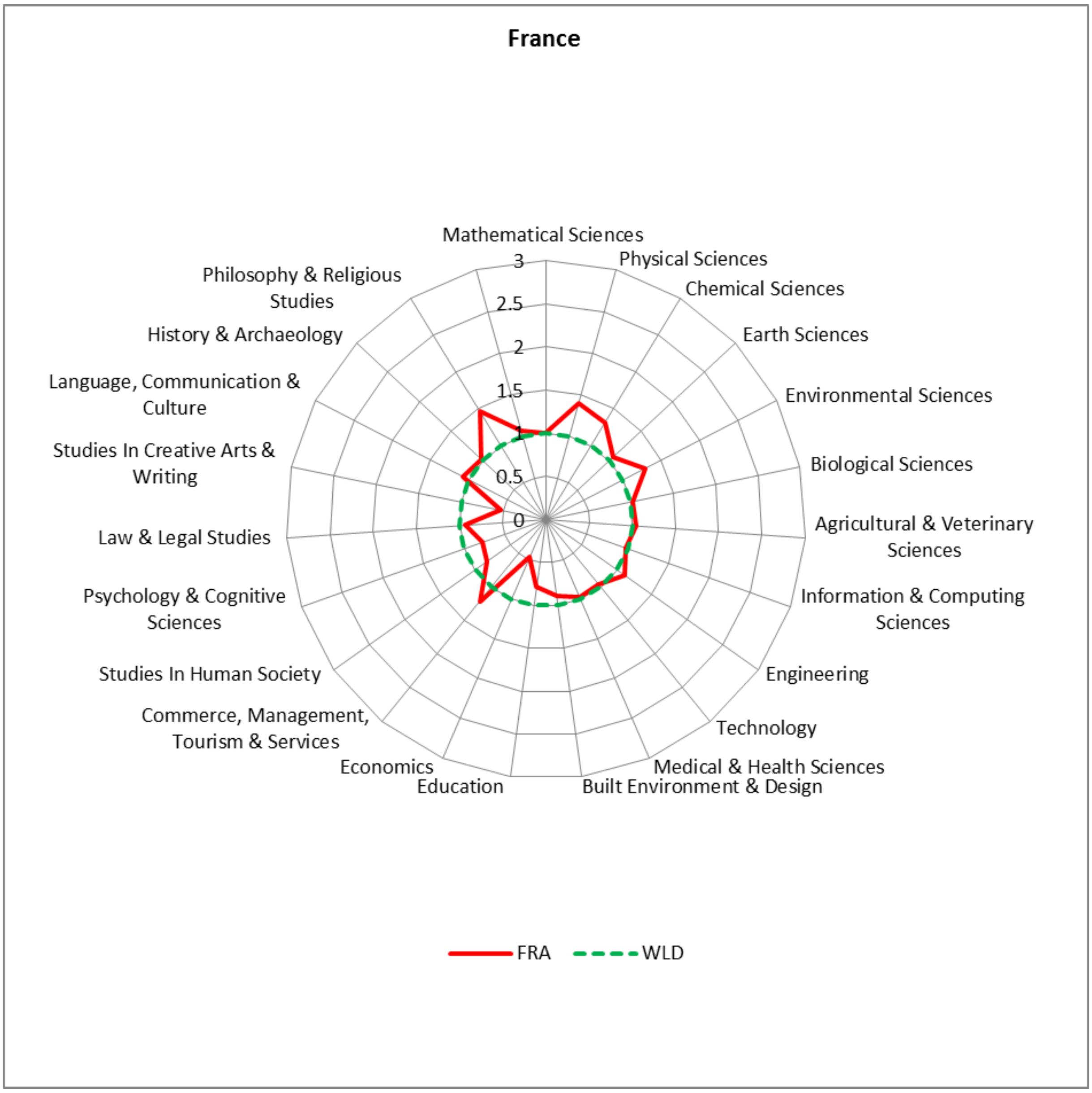
e. France


France
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Agricultural & Veterinary Sciences
Information & Computing Sciences
Engineering
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Medical & Health Sciences
Built Environment & Design
Education
Economics
Commerce, Management, Tourism & Services
Studies In Human Society
Psychology & Cognitive Sciences
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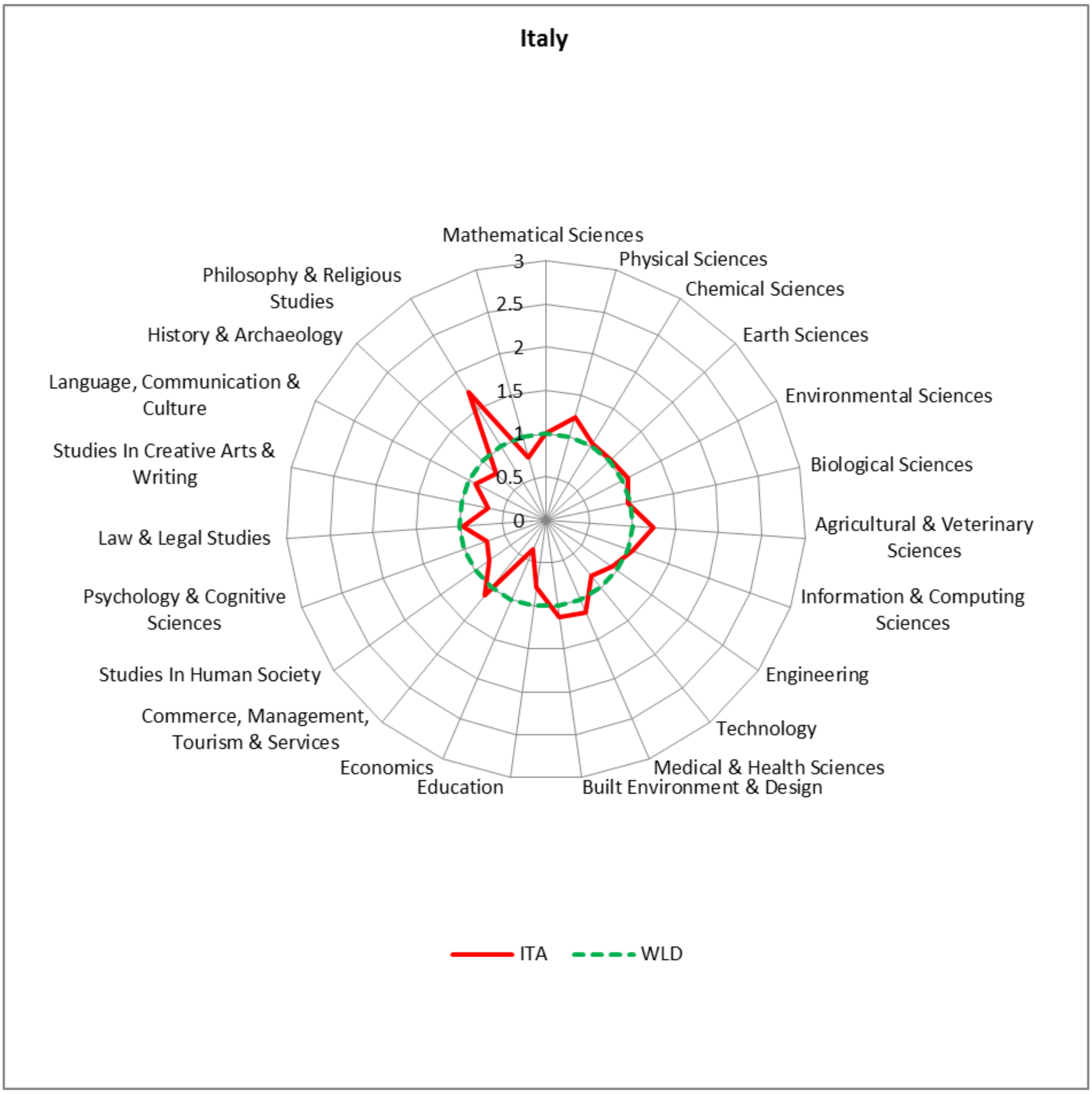
f. Italy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Built Environment & Design
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Psychology & Cognitive Sciences
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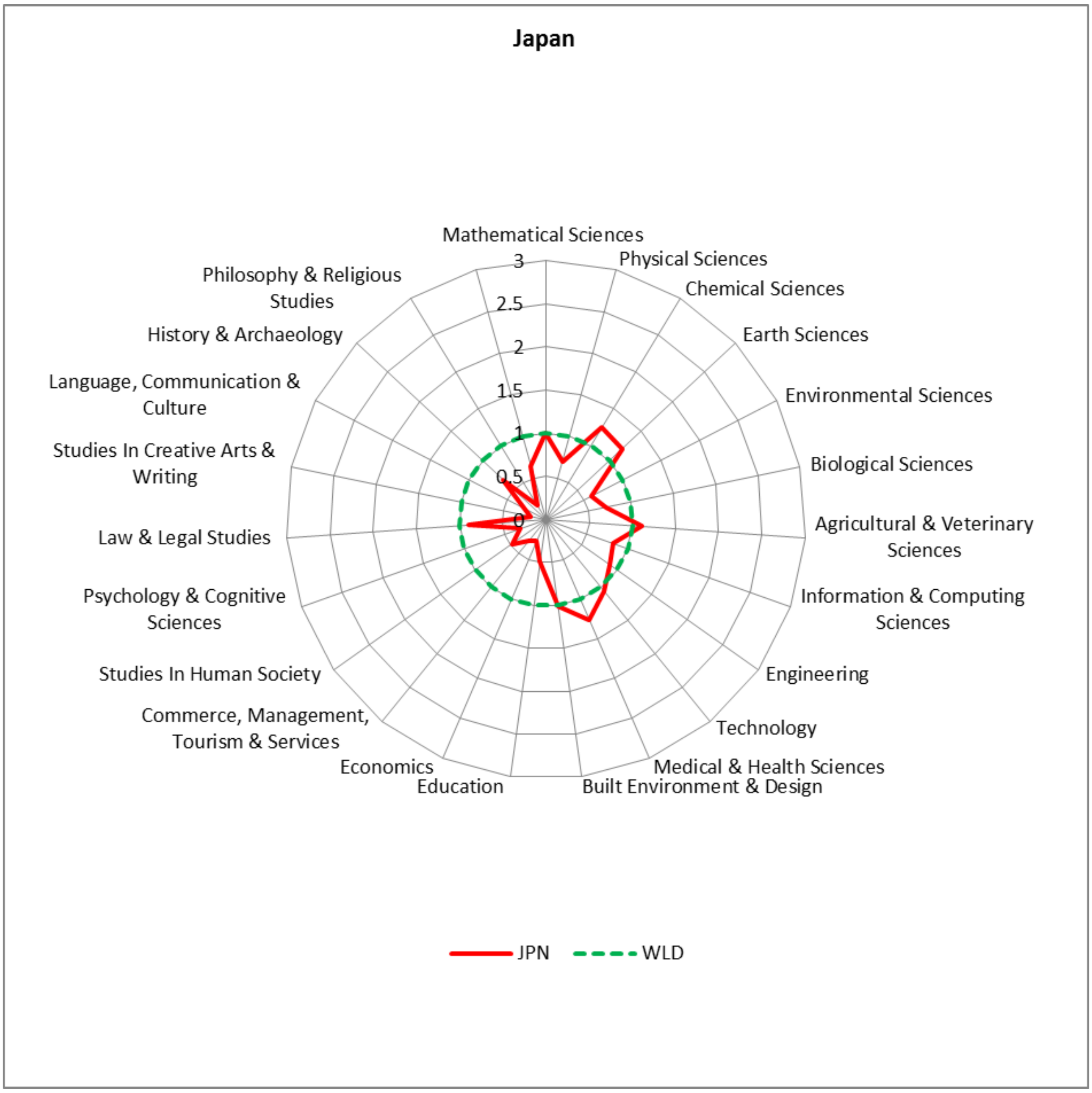
Japan
Mathematical Sciences
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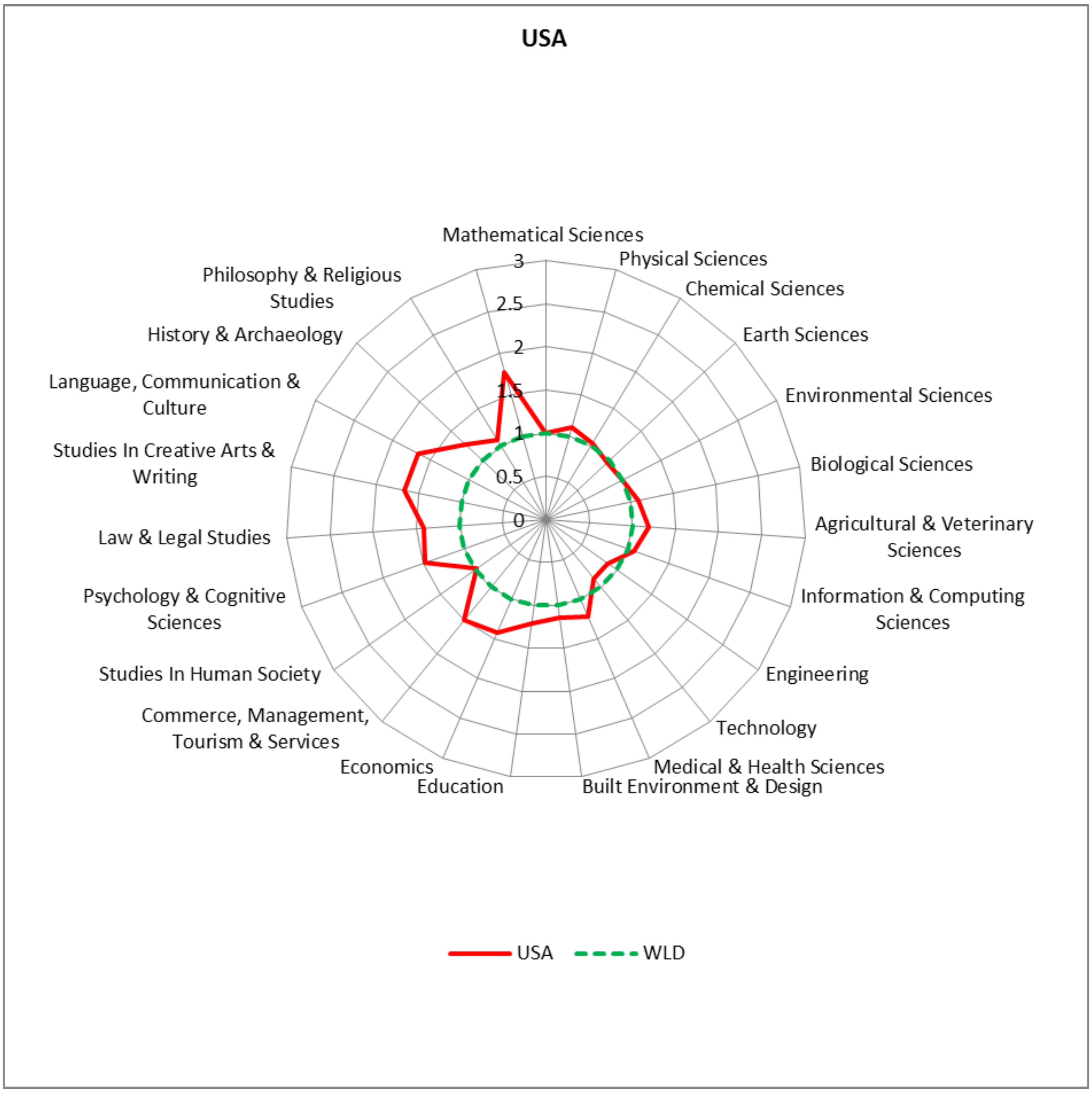
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Biological Sciences
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Built Environment & Design
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Studies In Human Society
Psychology & Cognitive Sciences
Law & Legal Studies
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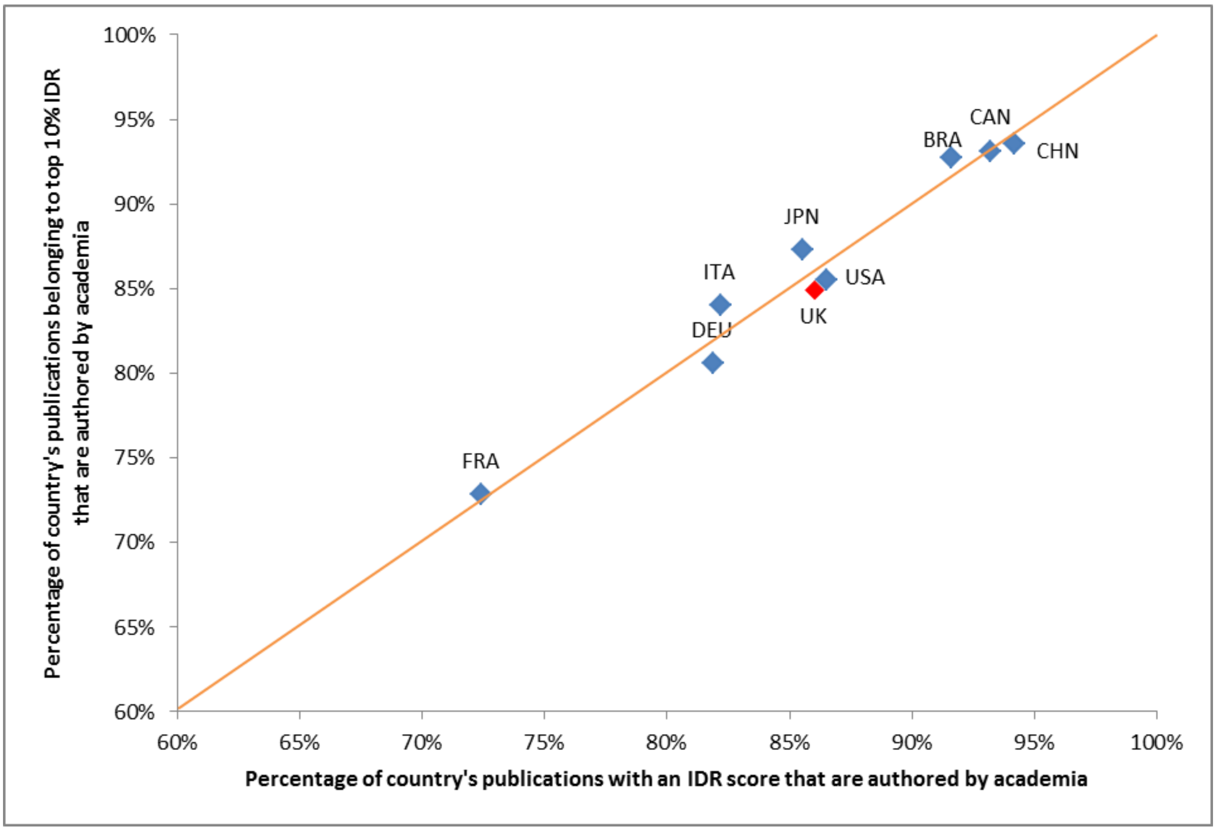
1.4 The great majority of top 10% IDR publications are authored by researchers in academia

43. The great majority of world publications are produced by researchers in academia including universities, colleges, and research centres. We can see from Figure 1.7 that, for the UK and the comparator countries, between 70% and 95% of all publications with an IDR score have at least one author from academia. China has the highest percentage (94%) and France the lowest one (72%). For the UK the proportion is 86%.[24]

44. Now we restrict our set of publications to the top 10% IDR publications. We see that the percentages change very little for all countries in Figure 1.7. Around 85% of the UK's publications that belong to the top 10% IDR have at least one author from academia. Researchers in academia contributed to the great majority of the top 10% IDR publications for the UK and comparator countries.

[24] One may argue that other sectors may contribute to a comparable percentage of publications as academia since publications may be collaborative efforts of various sectors. This however cannot be the case. Later in the report (Figure 3.6), we see that for most of the countries only a small percentage of publications are collaborative efforts between academia and other sectors.

+
Figure 1.7— *Percentage of publications that are authored by academia (comparison of publications that belong to top 10% IDR and publications with a score); all divisions; per country; for 2009-2013.*



What are the sectors publishing research?

Academic

► University: universities and other institutions that grant undergraduate, graduate, and/or Ph.D. degrees as well as engage in research. Examples: the University of Oxford, the University of Cambridge.

► College: institutions that grant undergraduate degrees as well as engage in research to some extent. Examples of colleges: Trinity Valley Community College (http://www.tvcc.edu/), Scottish Agricultural College (http://www.sruc.ac.uk)

► Research institute: organizations whose primary function is to conduct research and may include some educational activities but which are not universities. Example: Salk Institute, members of the Max-Planck Society (MPI of Biochemistry and others). Charity-funded research centres are also included in this category, e.g., the UK's National Eye Research Centre, Wellcome Trust and Cancer Research UK.

Medical

►Medical school: organizations that offer medical degrees as well as engage in research. Examples: Queen's Medical Centre, Harvard Medical School, Brown Medical School. We do not designate dental schools and providers of other health-related degrees as Medical schools.

► Hospital: organizations whose primary function is to provide health care, although they may also do research. Example: All Saints Hospital, St Mary's Hospital London, and Royal Brompton Hospital.

Corporate

► Company: commercial entities primarily operating with a profit motive, although some non-profit organizations could potentially be classified as companies. Examples: Unilever, British Broadcasting Corporation, Microsoft Research Cambridge, Royal Bank of Scotland, IBM, Hewlett-Packard.

► Law firm: business entities formed by one or more lawyers to engage in the practice of law. Examples: Baker and McKenzie (http://www.bakermckenzie.com/)

Government

► Government: includes all levels of government as well as United Nations. Example: US Department of Energy, Department for Business, Innovation & Skills, UK.

► Military organization: Example: UK Defence Science and Technology Laboratory, US Army Research Laboratory, Weapons and Materials Research Directorate.

45. The dominance of academia among other sectors in the top 10% IDR publications is also reflected in Table 1.1 that lists UK's top 20 organizations with the highest share of top 10% IDR out of the organization's total publications with an IDR score (panel 1) and UK's top 20 organizations with the largest number of top 10% IDR publications (Panel 2). The table shows the sector of the organization, the number of publications in the top 10% IDR, the number of publications with an IDR score, the ratio between the two, and the organization's total publications in Scopus.

46. Unilever, the British-Dutch multinational consumer goods company, leads with 18.4% of its publications belonging to top 10% IDR publications; it is also the only organization in the corporate sector on the list. Institute of Food Research leads the government organizations on the list. The list also includes a number of hospitals. In terms of the volume of top 10% IDR, University College London leads the UK's organizations with 3,714 top 10% IDR publications in the period of 2009-2013.

+
Table 1.1— *The top 20 UK organizations with the highest share of top 10% IDR out of the organization's total publications with an IDR score and with at least 250 publications with an IDR score in the period 2009-2013 (panel 1), and the top 20 UK organizations with the largest number of top 10% IDR publications (panel 2); all divisions for the UK; 2009-2013.*

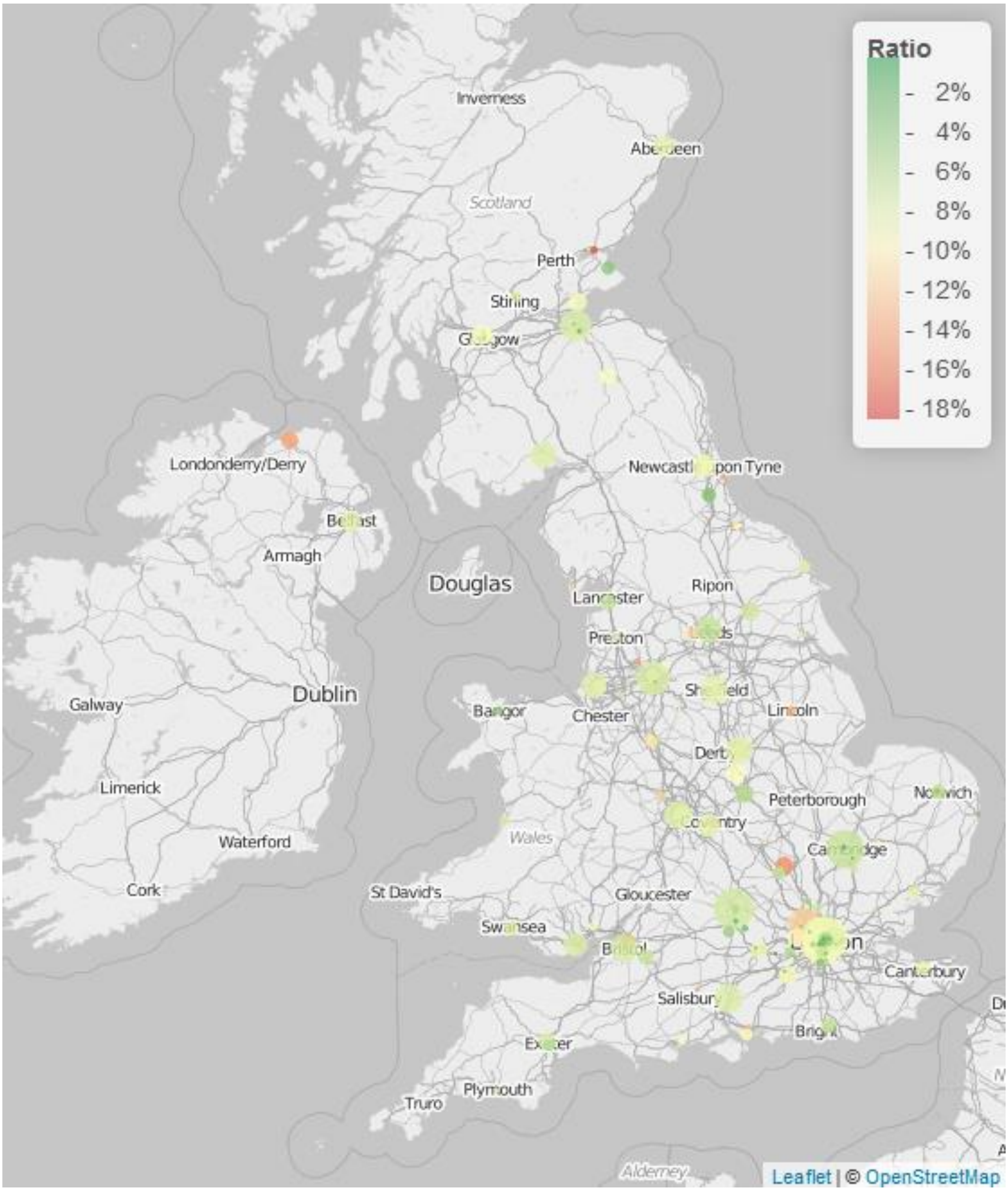
Institution name	Sector of the institution	Publications that belong to top 10% IDR (1)	Publications with an IDR score (2)	Ratio (1)/(2)	Total Publications
Panel 1: Top 20 organizations with the highest share of top 10% IDR out of the organization's total publications with an IDR score (at least 250 publications with an IDR score in the period 2009-2013)					
Unilever	Corporate	256	1388	18.4%	1435
University of Abertay Dundee	Academic	81	481	16.8%	546
Institute of Food Research	Government	105	629	16.7%	647
School of Pharmacy University of London	Academic	130	822	15.8%	853
University of the West of England	Academic	315	2048	15.4%	2412
Northwick Park Hospital	Medical	59	385	15.3%	423
Wythenshawe Hospital	Medical	48	317	15.1%	346
Birmingham City University	Academic	60	400	15.0%	545
Cranfield University	Academic	536	3699	14.5%	4290
Coventry University	Academic	198	1397	14.2%	1718
University of Greenwich	Academic	201	1439	14.0%	1701
Sheffield Children's Hospital	Medical	45	329	13.7%	353
University of Bolton	Academic	55	403	13.7%	502

University of Ulster	Academic	498	3657	13.6%	4088
National Institute for Biological Standards and Control	Government	39	292	13.4%	321
University of Sunderland	Academic	54	409	13.2%	505
City Hospital in Birmingham	Medical	62	471	13.2%	534
University of Lincoln	Academic	155	1204	12.9%	1353
Defence Science and Technology Laboratory	Government	33	260	12.7%	327
Queen Alexandra Hospital	Medical	54	427	12.7%	496
Panel 2: Top 20 organizations with the largest number of top 10% IDR publications					
University College London	Academic	3714	41229	9.0%	44691
University of Oxford	Academic	3043	40034	7.6%	43930
Imperial College London	Academic	2932	30573	9.6%	41389
University of Cambridge	Academic	2663	37670	7.1%	32928
University of Manchester	Academic	2100	26684	7.9%	29408
King's College London	Academic	2089	23801	8.8%	25964
University of Edinburgh	Academic	1783	22316	8.0%	24295
National Health Service Blood and Transplant	Government	1635	14244	11.5%	20588
University of Southampton	Academic	1479	18479	8.0%	19658
University of Bristol	Academic	1394	18100	7.7%	18661
University of Birmingham	Academic	1388	17054	8.1%	18740
University of Sheffield	Academic	1374	16534	8.3%	18208
University of Nottingham	Academic	1346	16247	8.3%	17909
University of Glasgow	Academic	1225	15231	8.0%	16832
University of Leeds	Academic	1215	17045	7.1%	16761
University of Liverpool	Academic	1165	13972	8.3%	15353
NHS Foundation Trust	Hospital	1043	9597	10.9%	13582
Cardiff University	Academic	998	12567	7.9%	13136
Newcastle University	Academic	996	11307	8.8%	12254
Queen Mary, University of London	Academic	984	11991	8.2%	12277

47. In Figure 1.8, we plot the UK's organizations with at least 250 top 10% IDR publications in the period 2009-2013. The size of the circles denotes the number of top 10% IDR publications. We see big circles around London, Oxford, Cambridge, Edinburgh and Manchester. For most of the larger circles in Figure 1.8, the share of top 10% IDR publications out of all of the institution's publications with an IDR score is between 7% and 12%. Among the UK's top 20 organizations with the largest number of top 10% IDR publications, National Health Service Blood and Transplant leads in the top 10% IDR share (11.5%).

+

Figure 1.8— *UK institutions with at least 250 publications with an IDR score in the period 2009-2013; all divisions; 2009-2013. The size of the circles denotes the number of top 10% IDR publications and the colour denotes the share of top 10% IDR publications out of all of the institution's publications with an IDR score.*[25]



[25] The chart was produced by Georgin Lau using the Leaflet package distributed under GPL-3 (GNU GENERAL PUBLIC 2 LICENSE version 3).

Chapter 2
Citation Impact and Usage of IDR

This chapter summarises the findings on the citation impact and usage of IDR publications. It investigates three indicators that measure the quality of research from different perspectives: field-weighted citation impact (FWCI), field-weighted download impact (FWDI), and relative citations in patent applications.

2.1 Key findings

CITATION IMPACT OF UK PUBLICATIONS THAT BELONG TO TOP 10% IDR

1.35

In 2013, the FWCI of the UK's publications that belong to the top 10% IDR is 1.35, lower than that of all of the UK's publications with an IDR score (1.71).

DOWNLOAD IMPACT OF UK PUBLICATIONS THAT BELONG TO TOP 10% IDR

1.07

In 2013, the FWDI of the UK's publications that belong to the top 10% IDR is 1.07, lower than that of all of UK's publications with an IDR score (1.20).

CITATIONS IN PATENT APPLICATIONS

Germany

For many comparator countries, top 10% IDR publications are more frequently cited in patent applications than in all publications with an IDR score. Germany leads all comparator countries on this indicator: in 2013, its top 10% IDR publications are cited 2.24 times more frequently in patent applications than the world average.

2.2 Top 10% IDR has lower citation impact than all publications with an IDR score

48. We introduce an indicator named "field-weighted citation impact" (FWCI) to measure the citation impact of publications. FWCI takes into consideration the fact that publications in different subject areas, published in different years, and with different document types will on average receive a very different number of citations. Therefore, the citation numbers need to be normalized by the average citations of publications with the same subject area, year, and document type in order to be comparable across these three dimensions. The world average is 1 for this indicator. This measure of citation impact may be more applicable to disciplinary research than IDR. As mentioned earlier, FWCI normalizes the citation counts of a publication by the average citations of publications in the same subject area. The subject classification is based on the journal classification. If an IDR publication is published in a disciplinary journal, normalizing its citations by the average citations of the subject area of the journal does not fully account for the fact that the IDR publication spans multiple disciplines.

49. Our results show that the FWCI of publications that belong to the top 10% IDR is lower than that of all publications with an IDR score. We can see in Figure 2.1 that this conclusion holds for the UK and all comparator countries. Nevertheless, it should be noted that the UK's research is of high and stable quality. In 2013, the FWCI of the UK's publications is the highest among comparator countries, whether looking at all publications with an IDR score or those in the top 10% IDR publications. The FWCI of the former group is 1.71, and the latter is 1.35. Both of these values are well above the world average of 1. We also see that while the USA's FWCI dropped significantly from 2009 to 2013, the UK's FWCI remained very stable.

50. China, Brazil and Japan have the lowest FWCI. This implies that despite China and Brazil's high percentage of top 10% IDR out of their total publications with an IDR score, the citation impact of these IDR publications remain relatively low.

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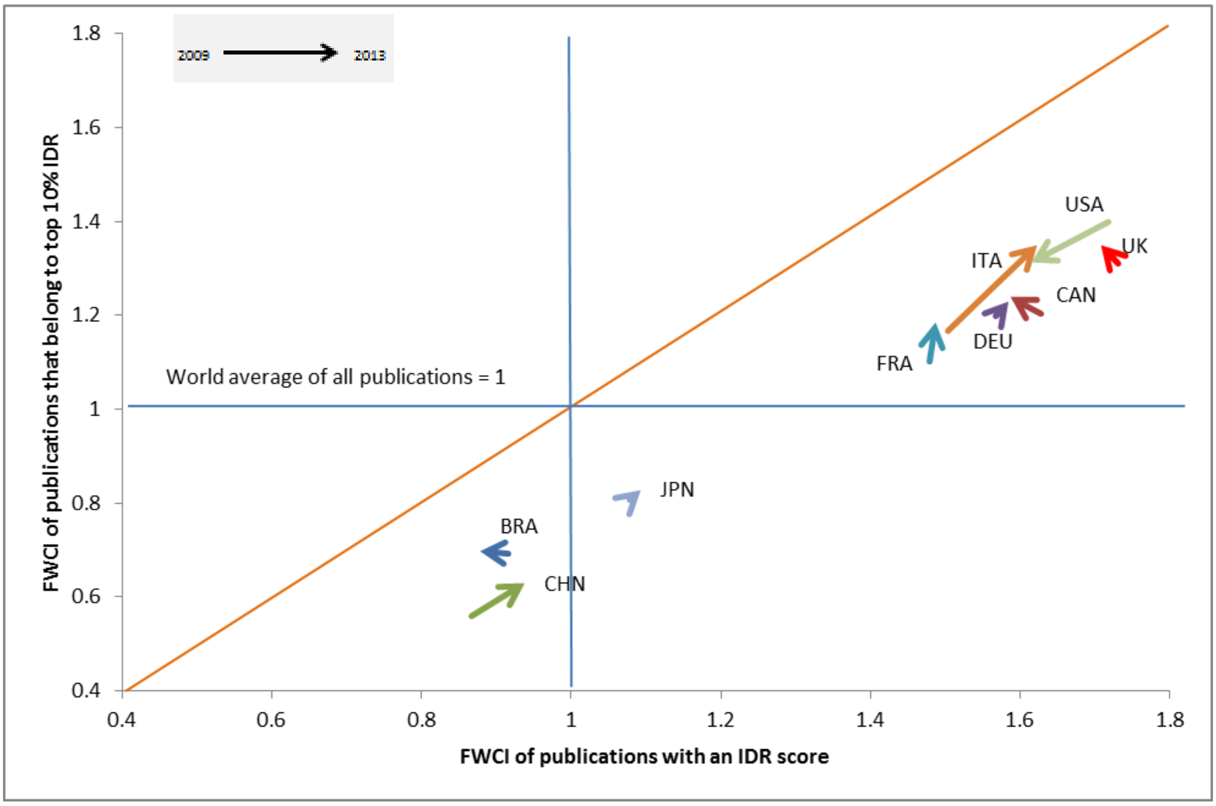
Figure 2.1— *FWCI of publications with an IDR score and FWCI of top 10% IDR; all divisions; per country; for 2009 and 2013.*



Field-weighted citation impact

Citations accrue to published articles over time, as articles are first read and subsequently cited by other authors in their own published articles. Citation practices, such as the number, type, and age of articles cited in the reference list, differ by research field. As such, in comparative assessments of research outputs citations must be counted over consistent time windows, and publication and field-specific differences in citation frequencies must be accounted for.

Field-weighted citation impact is an indicator of mean citation impact, and compares the actual number of citations received by an article with the expected number of citations for articles of the same document type (article, review, or conference proceeding paper), publication year, and subject field. Where the article is classified in two or more subject fields, the harmonic mean of the actual and expected citation rates is used. The indicator is therefore always defined with reference to a global baseline of 1.0 and intrinsically accounts for differences in citation accrual over time, differences in citation rates for different document types (reviews typically attract more citations than research articles, for example), as well as subject-specific differences in citation frequencies. FWCI is one of the most sophisticated indicators in the modern bibliometric toolkit.

To count citations, a 5-year window is used. For publications in 2009, their citations in the five-year period 2009-2013 are counted. For publications in 2013, their citations to date are counted.

51. To explore further the relation between IDR publications and their FWCI, we provide a breakdown by divisions for the UK in Figure 2.2a and Figure 2.2b. Again for most of the divisions, the FWCI of the top 10% IDR is lower than that of all publications with an IDR score. The two exceptions are Economics and Law & Legal Studies, but these two divisions have a low absolute number and percentage of top 10% IDR publications for the UK.

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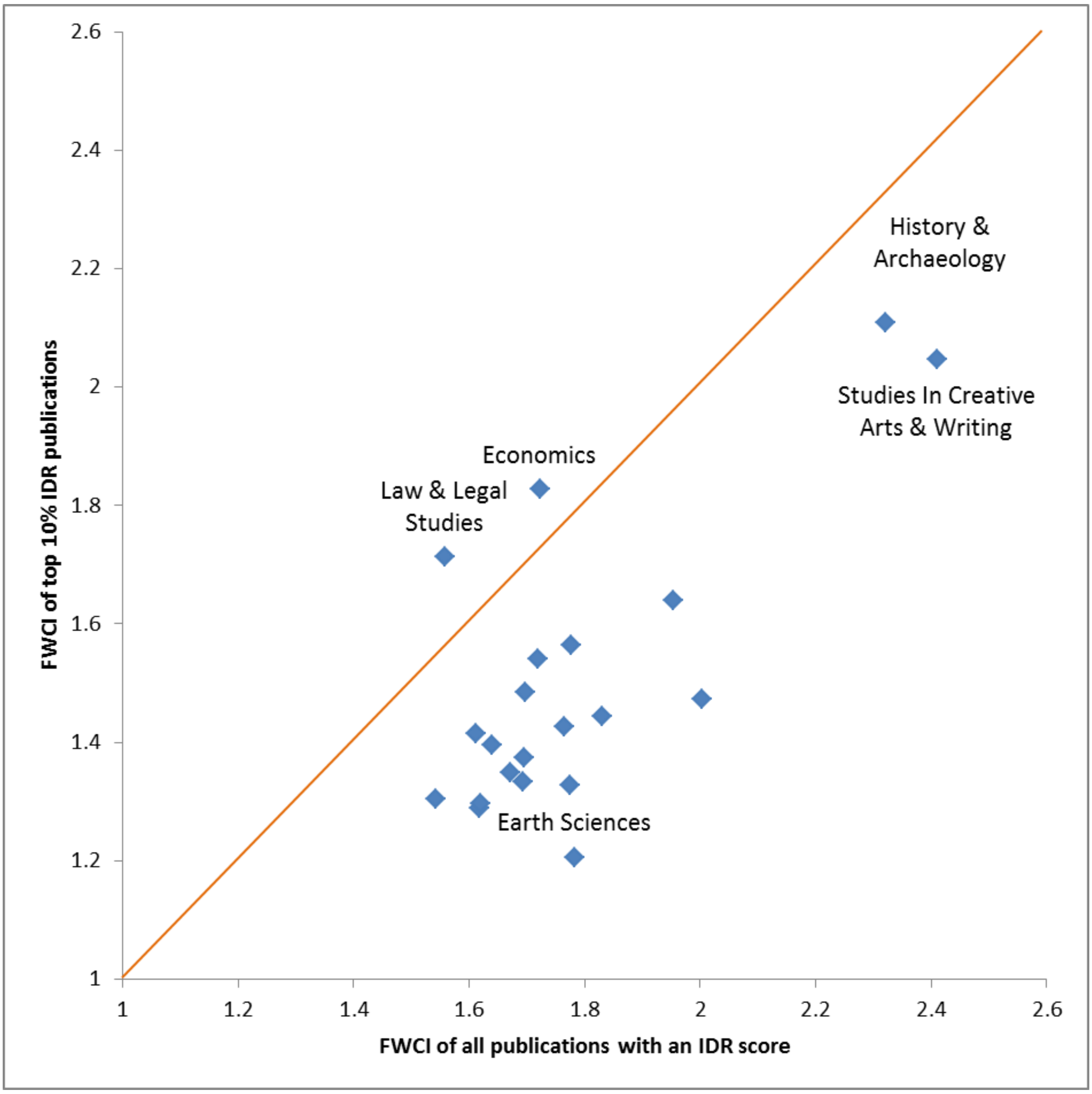
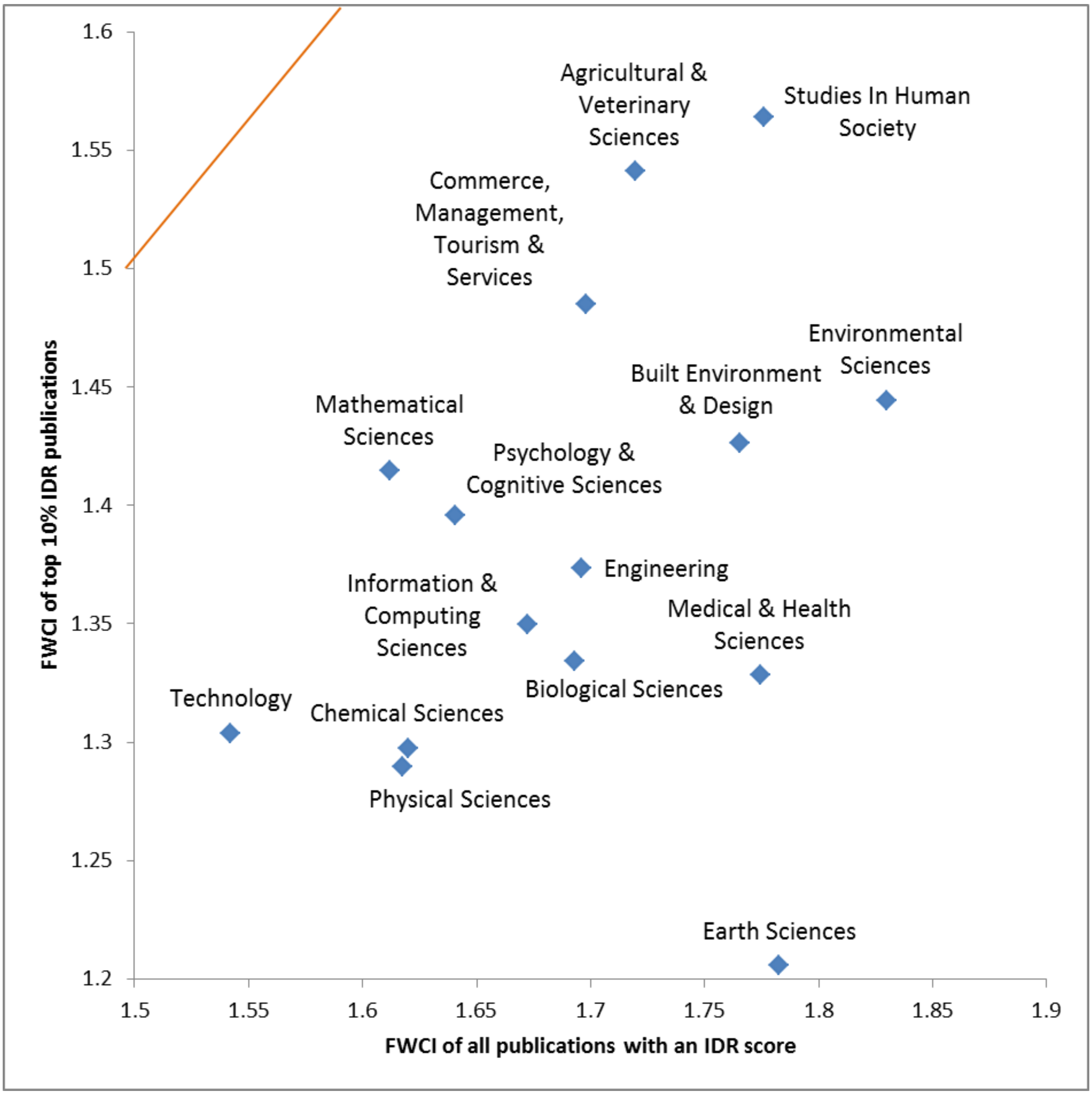
Figure 2.2— *FWCI of publications with an IDR score and FWCI of top 10% IDR; per division; for the UK; 2009-2013.*

a. All divisions



b. A zoom in on Figure 2.2a



52. It is beyond the scope of this report and our data to find out what led to the lower citation impact of IDR publications. There is also no consensus from the literature on whether IDR publications receive more or fewer citations than monodisciplinary ones do. Advocates argue that IDR stimulates innovation in research by integrating knowledge from multiple disciplines.[26] Breakthroughs in research are likely to happen

[26] See for example:

- Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., and Trow, M. (1994). *The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies*. Sage, London.

when concepts, methods, and data are synthesized from different disciplines by challenging established beliefs.[27] Therefore, IDR publications are expected to be associated with higher citation impact. However, others accuse IDR of lacking disciplinary notions of quality[28]. Bruce et al. (2004) reported the difficulties in managing the coordination and integration of distributed knowledge, and institutional and organisational barriers such as relatively poor career prospects, discrimination by reviewers in proposals, and disproportionately high difficulty in publishing in prestigious journals.[29] When IDR involves teamwork, the need to mix knowledge and to get all members in an IDR team to understand the results may also reduce the quality and depth of monodisciplinary analysis. In this view, IDR publications may suffer from a lack of quality. As citation impact is often used in bibliometrics as an indication of quality, it can be argued that this is a reason why the citation impact of IDR publications is lower.

53. Another plausible explanation for our finding that IDR publications are associated with lower citation impact is the delayed recognition of IDR. Wang, Thijs, and Glänzel (2015)[30] found that IDR is associated with lower citation impact in the short term (three years) and higher citation impact in the long term (13 years). Our finding is in line with the first part of the conclusion, since we use a five-year period which is closer to

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- Heinze, T., Shapira, P., Rogers, J. D., and Senker, J. M. (2009). Organizational and institutional influences on creativity in scientific research. *Research Policy* 38, 610-623.
- Hemlin, S., Allwood, C. M., and Martin, B. R. (Eds) (2004). *Creative knowledge environments: the influences on creativity in research and innovation.* Edward Elgar, Cheltenham, UK.

[27] See for example, Hollingsworth, R., and Hollingsworth, E.J. (2000) Major discoveries and biomedical research organizations: perspectives on interdisciplinarity, nurturing leadership, and integrated structure and cultures, in: Weingart, P., and Stehr, N. (Eds), *Practising Interdisciplinarity*. University of Toronto Press, Toronto, pp. 215-244 and Barry, A., Born, G., and Weszkalnys, G. (2008) Logics of interdisciplinarity. *Economy and Society* 37, 1, 20-49.

[28] See discussions in Rafols, I., Leydesdorff, L., O'Hare, A., Nightingale, P., and Stirling, A. (2012). How journal rankings can suppress interdisciplinary research. A comparison between innovation studies and business & management. *Research Policy* 41 (7), Pages 1262-1282.

[29] Bruce, A., Lyall, C., Tait, J., and Williams, R. (2004). Interdisciplinary integration in Europe: the case of the Fifth Framework programme. *Futures* 36, 457-470.

[30] Wang, J., Thijs, B., and Glänzel, W. (2015) Interdisciplinarity and Impact: Distinct Effects of Variety, Balance, and Disparity. PLoS ONE 10(5): e0127298. doi:10.1371/journal.pone.0127298.

the short term. It will be interesting for future study to test the long-term case.

2.3 Downloads and patent citations of the top 10% IDR publications

54. Although citations are an important measure of research impact, there are some drawbacks. Citations take time to accumulate, so that they are not the best indication of the immediate interest in publications.

55. Additionally, citations only partially capture the usage of research output, since not all publications that are accessed and read by researchers (or other readers) are cited in later articles.

56. Full text article download data from Elsevier's ScienceDirect database (which provides approximately 20% of the world's published journal articles) offers one option to measure the extent of this usage. The number of publication downloads from a particular subject area, institution, or country may be interpreted as representing the use of research.

57. Similar to FWCI, we introduce an indicator named "field-weighted download impact" (FWDI) as a measure of download impact. It normalizes downloads by the average number of downloads received by publications with the same subject area, year, and document type.[31]

[31] Similar to FWCI, the subject normalization used to calculate FWDI may be more precise for monodisciplinary publications than for the interdisciplinary ones.

Downloads and FWDI

A download is defined as the event where a user views the full-text HTML of an article or downloads the full-text PDF of an article from ScienceDirect, Elsevier's full-text journal article platform; views of an article abstract alone, and multiple full-text HTML views or PDF downloads of the same article during the same user session, are not included in accordance with the COUNTER Code of Practice 35. ScienceDirect provides download data for approximately 20% of the articles indexed in Scopus; it is assumed that user downloading behaviour across countries does not systematically differ between online platforms. FWDI is calculated from these data according to the same principles applied to the calculation of field-weighted citation impact.

Similar to citations, a 5-year window is used to count downloads received by a publication.

58. Figure 2.3 compares the FWDI of top 10% IDR to that of all publications with an IDR score. Similar to FWCI, for all countries the former is lower than the latter; implying that IDR is not associated with a higher level of downloads. The UK stands out in this figure, leading comparator countries in both FWDI numbers. We also note that for all countries except Japan, the FWDI is above the world average of 1 in all years in the period of 2009-2013, when we look at publications with an IDR score. This number falls below the world average for most of the countries except for the UK and Italy, when we restrict the publication set to the top 10% IDR.

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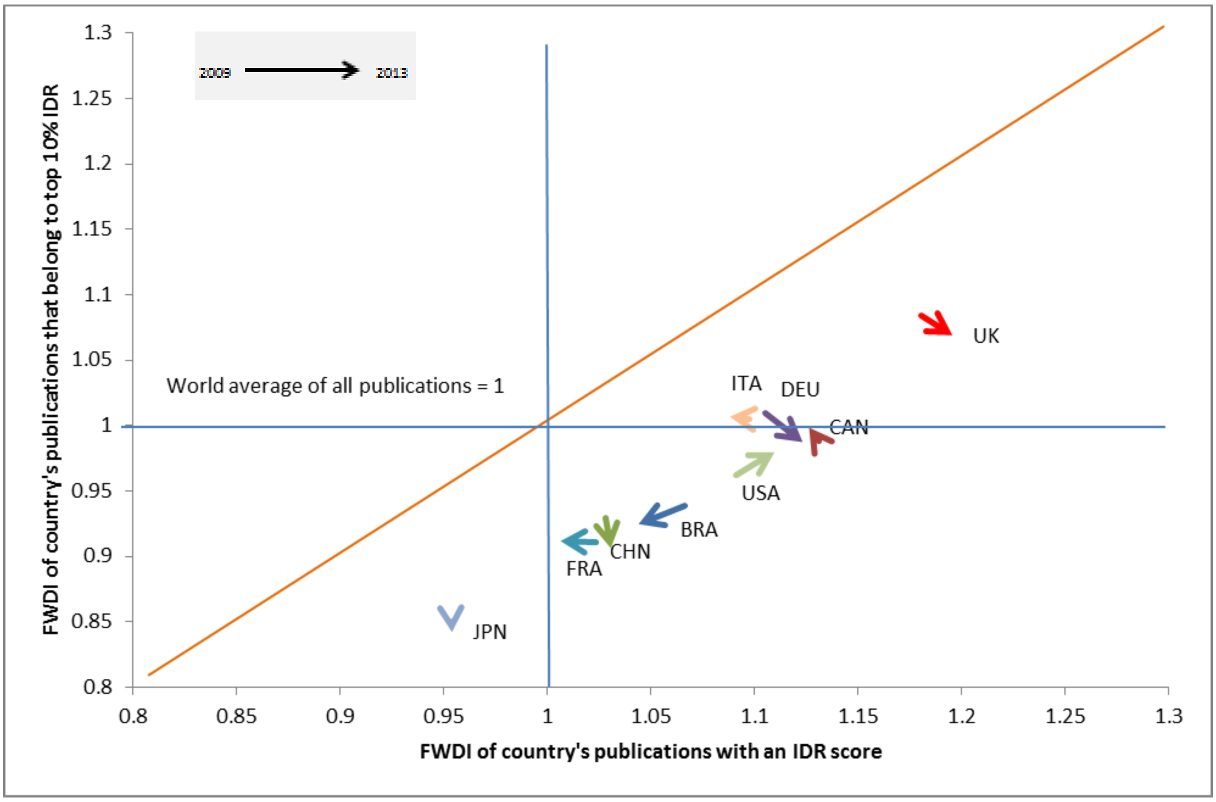
Figure 2.3— *FWDI of publications with an IDR score and FWDI of top 10% IDR; all divisions; per country; for 2009 and 2013.*



59. While downloading and reading publications are necessary conditions for scientific publications to be used in technology development, the relation between science and technology is complex; over the last decades, the two have become closely intertwined. The use of scientific publications in technology development has become an essential dimension of research impact.

60. Citations of scientific publications in patent applications provide a way to measure the use of publications in technology development. Large countries tend to have a large number of publications, and therefore also a large number of citations of publications in patents. For our indicator to be comparable across countries, we first calculate the world patent citation share of each comparator country. For example, the UK's patent citations represent around 11.1% of world patent citations in 2013. We then normalize this number by the UK's publication share of 6.9% in 2013. The UK's relative patent citation share is then equal to 11.1%/6.9%=1.61 in 2013. This implies that relative to its publication share, the UK's publications are cited 1.6 times more often in patent applications than the world average.

61. Performing the same calculation for the top 10% IDR publications of the UK, we see that the relative patent citation share is slightly higher (1.63). This implies that the UK's publications that belong to the world top 10% IDR are more frequently cited in patent applications than in all UK's publications with an IDR score. We can see from Figure 2.4 that with the exception of France, Japan and China, this conclusion holds for all other comparator countries for at least one of the two plotted years (2009 and 2013). Germany stands out, leading in both relative patent citation share numbers in all years.[32]

62. IDR benefits the application of research publications to technology development measured by patent applications, even though IDR publications are not more likely to be produced by researchers outside of academia (see Figure 1.7) and they do not receive higher overall numbers of citations. One plausible explanation is that IDR includes more applied research (e.g., agriculture and food research), so that the barriers to application in technology tend to be reduced for IDR research. This will be an area for further research.

[32] One may argue that the reason Germany holds a leading position in this indicator is because a larger share of its publications belongs to divisions that are more likely to be cited in patent applications. The division distribution of Germany's publications however cannot fully explain the finding in Figure 2.4. We reproduced this figure after restricting publications to the divisions Technology and Engineering, both of which are likely to be cited in patent publications. We see that Germany still leads the comparator countries in this indicator.

Patents and patent citations

The patenting process can be divided into three distinct phases: filing an application for a patent and its examination; the registration of a decision (granted or not); and the on-going payment of maintenance fees to keep the patent in force. Data indicating the volume of patenting activity in each of these phases are available: patent applications, patents granted, and patents in force.

It is important to note that these counts for patent applications, patents granted, and patents in force are totals, aggregated across all fields of research and all sectors of research and development performance. However, not all research fields and sectors have the same propensity to patent, and so national patenting activities may reflect national research field specialisation and industry focus.

Patent citations count the number of scientific publications referenced in patent applications.

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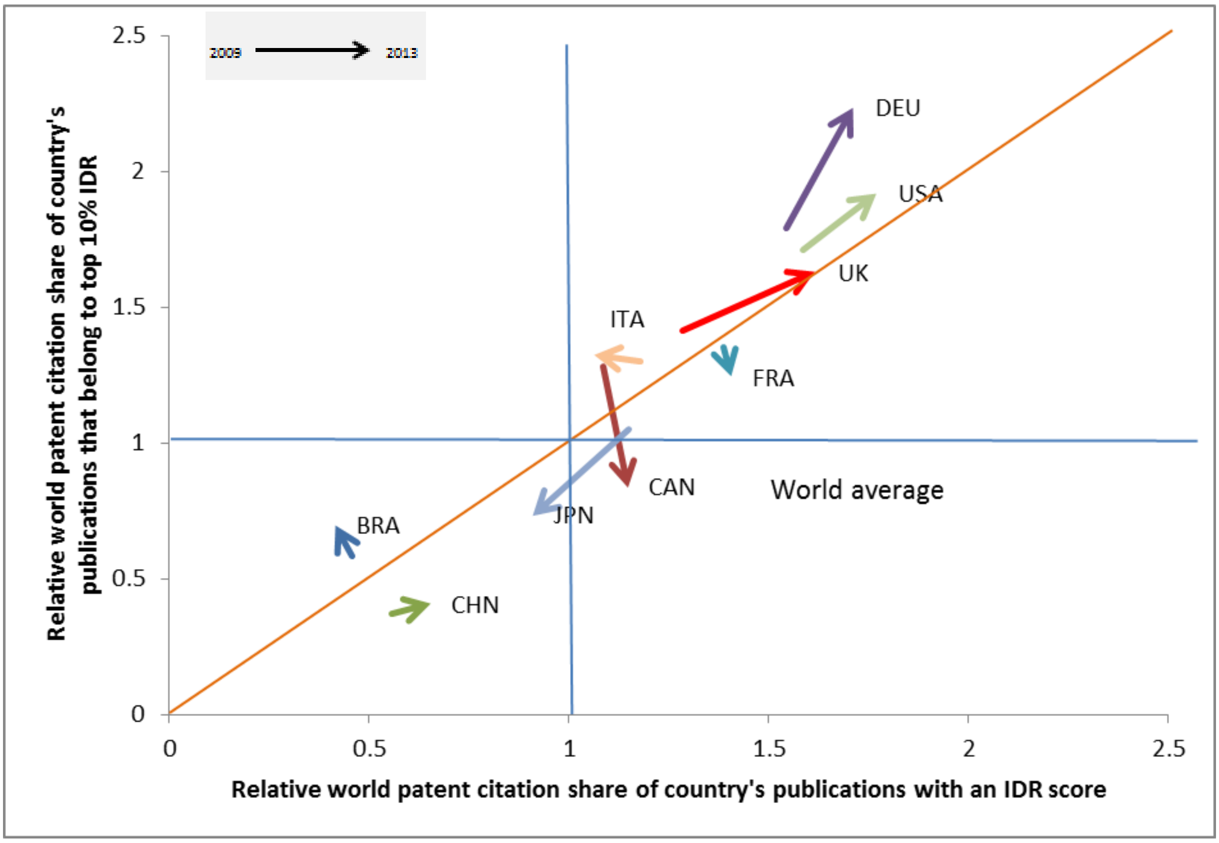
Figure 2.4— *Relative world patent citation share of publications with an IDR score and of top 10% IDR; all divisions; per country; for 2009 and 2013.*



Chapter 3

Collaborations in IDR

This chapter summarises the findings in collaboration in IDR. It looks at three aspects of collaboration: collaboration between each pair of divisions, geographic collaboration, and collaboration across sectors.

3.1 Key findings

INTERNATIONAL COLLABORATION

45.5%

In 2009-2013, around 45.5% of the UK's publications that belong to the top 10% IDR involve international collaboration. This percentage is lower than that of all of the UK's publications with an IDR score (50.6%).

ACADEMIC-CORPORATE COLLABORATION

4.7%

In 2009-2013, around 4.7% of the UK's publications that belong to the top 10% IDR involve collaboration with industry. This percentage is slightly (but not significantly) lower than that of the UK's total publications with an IDR score (4.9%).

MOST FREQUENTLY COLLABORATED DIVISIONS IN IDR

Chemical Sciences and Biological Sciences

In the period of 2009-2013, there are in total 119,417 publications co-authored by researchers from the Chemical Sciences and the Biological Sciences.

3.2 Collaboration between divisions in IDR

63. IDR often involves researchers from different disciplines collaborating together. Between which divisions do researchers collaborate most intensively?

64. Figure 3.1 shows the divisions in a network map. Scopus author profiles are used to identify collaboration across divisions. If a publication has two authors, and one published the largest number of publications in division A and the other in division B, this publications is classified as a collaborative publication between divisions A and B.[33] Divisions where researchers collaborate more intensively are plotted closer to each other. Table 3.1 lists the top 10 pairs of divisions with the highest level of collaboration intensity. It is clear from the figure and the table that divisions with the most intensive level of collaboration concentrate in the research domains Natural Sciences and Engineering & Technology. The Chemical Sciences and the Biological Sciences lead on this indicator. While each of them has around 150,000 publications that belong to world's top 10% most IDR publications, around 119,000 publications are co-authored by at least one author whose main division is the Chemical Sciences and at least another author with main division Biological Sciences. The collaboration intensity is in general lower between divisions in the Social Sciences and the Humanities and between these divisions and those in the Natural Sciences.[34]

[33] The collaborative relationship therefore only depends on the journal classification of the authors' publications.
[34] It is possible that collaboration measured by co-authorship applies better to some disciplines than others. For example, in Arts & Humanities multiple single-authored articles might sometimes be the output of a multi/interdisciplinary large-scale collaboration rather than a co-authored article.

Collaboration intensity between divisions

We first assign each author a division in which the author publishes the majority of his/her publications. We then assign each publication to divisions based on the divisions of its authors. One publication may be assigned to multiple divisions if its authors belong to multiple divisions. For each pair of divisions, we count the number of co-authored publications between the two divisions.

We need to correct for the size of the division because large divisions tend to have more co-authored publications in absolute terms. Without correcting for the size of the divisions, large divisions will always appear to collaborate closely with each other. We use a cosine similarity index calculated using the following formula as a measure of collaboration intensity:

$$\frac{\text{co-authored top 10\% IDR publications between divisions A and B}}{\sqrt{\text{top 10\% IDR publications of division A} \times \text{top 10\% IDR publications of division B}}}$$

+
Figure 3.1— *Collaboration network map between divisions in IDR; all divisions; for the world; 2009-2013. The thickness (from thin to thick) and the colour (from light to dark) of the edges indicate the collaboration intensity. The size of the nodes (from small to big) indicates the number of publications of the division that belong to world's top 10% IDR.*

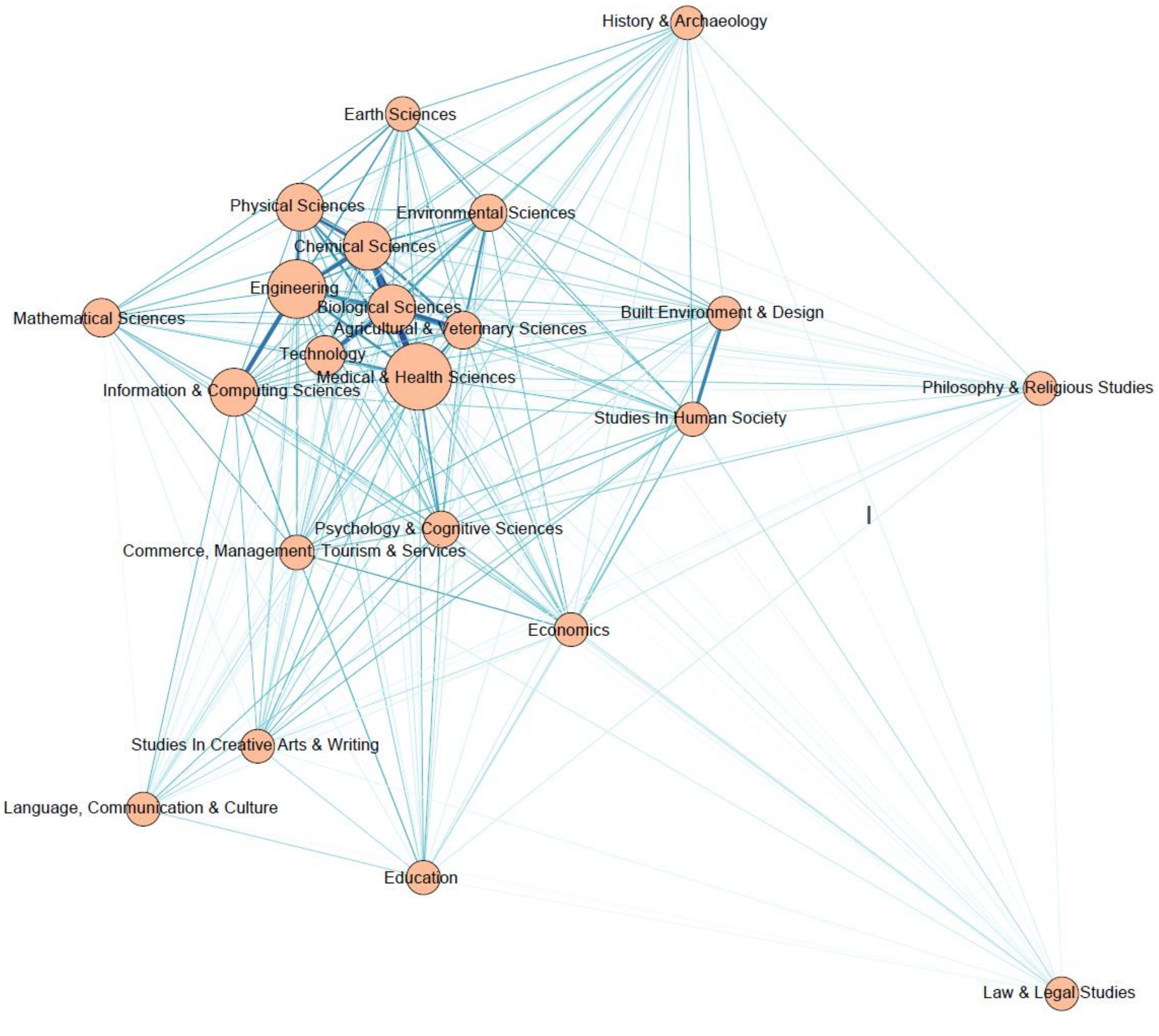


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Table 3.1 — *Top 10 pairs of divisions with the highest level of collaboration intensity; for the world; 2009-2013.*

Division A	Division B	Top 10% IDR publications division A	Top 10% IDR publications division B	Co-authored publications between divisions A and B	Collaboration intensity
Chemical Sciences	Biological Sciences	157,773	152,106	119,417	0.77
Biological Sciences	Medical & Health Sciences	152,106	354,697	139,159	0.60
Biological Sciences	Agricultural & Veterinary Sciences	152,106	47,856	40,763	0.48
Physical Sciences	Chemical Sciences	150,655	157,773	71,411	0.46
Chemical Sciences	Engineering	157,773	265,459	83,199	0.41
Physical Sciences	Engineering	150,655	265,459	80,651	0.40
Information & Computing Sciences	Engineering	153,848	265,459	78,595	0.39
Chemical Sciences	Medical & Health Sciences	157,773	354,697	91,462	0.37
Biological Sciences	Technology	152,106	71,773	39,663	0.38
Built Environment & Design	Studies In Human Society	6,676	8,188	2,268	0.31

3.3 International collaboration in IDR

65. Sonnenwald (2006)[35] discusses three types of research collaboration: disciplinary focus (e.g., interdisciplinary or monodisciplinary), geographic focus (e.g., international or national collaboration), and organizational and community focus (e.g., academic-corporate collaboration). Does interdisciplinary collaboration naturally lead to other types of collaboration? For example, is IDR associated with higher levels of collaboration with the international research community or the corporate sector? This section explores these dimensions.

66. The world is becoming smaller, with better developed transportation and communication modes. Leydesdorff (2013)[36] found that between 40 and 50 countries appeared in the centre of the network of international research collaboration in 2011, and almost all nations are nowadays involved in some form of international collaboration.

67. We categorize collaborations into four types depending on the number and geographic distribution of the authors: international, national, institutional, and single author.

[35] Sonnenwald, D. H. (2007). Scientific collaboration. *Annual Review of Information Science and Technology*, 41(1), 643–681.
[36] Leydesdorff, L., Wagner, C., Park, H. W., and Adams, J. (2013) International Collaboration in Science: The Global Map and the Network, *El Profesional de la Información* 22(1), 87-94.

Collaboration types

- An article is defined as an internationally collaborated article when authors affiliated with institutions from at least two different countries are listed in the authorship by-line.
- National collaboration occurs when authors are affiliated with different institutions within one country.
- When two or more authors are affiliated with the same institution and none of the authors are affiliated with other institutions, the article is counted as an institutionally collaborated article.
- A single-authored article is technically not a geographic collaboration type but serves as a benchmark.

68. As observed in many previous studies, research in the UK is highly international.[37] Figure 3.2 and Figure 3.3 confirm this conclusion: around 50.6% of the UK's publications with an IDR score in the period 2009-2013 are co-authored with international colleagues. This percentage ranks 2nd among comparators, below only France's 51.8%. In general European countries have the highest percentage of internationally collaborative publications. Emerging countries and East Asian countries have relatively lower percentages (China, Brazil, and Japan). The USA is in between the two groups because of intensive collaboration within the country.

69. It is clear from Figure 3.3 that IDR is not necessarily associated with higher levels of international collaboration: for all countries, the share of internationally collaborative publications declines if we restrict the publication set to the ones that belong to top 10% IDR. The difference of the international collaboration share between the top 10% IDR and all publications with an IDR score is significant at the 5% level for all comparator countries using a Binomial Proportion Test.[38]

70. For the UK, 45.5% of its publications that belong to the top 10% IDR are internationally collaborative (Figure 3.2). Out of

[37] See for example Elsevier reports "International Comparative Performance of the UK Research Base – 2013: A report prepared by Elsevier for the UK's Department of Business, Innovation and Skills (BIS)." Available at https://www.gov.uk/government/publications/performance-of-the-uk-research-base-international-comparison-2013

[38] The significance applies to Figure 3.2 as well for all collaboration types for the UK. Confidence intervals are very small and would not be visible on Figure 3.2 and Figure 3.3, and are therefore not shown.

these publications in the top 10% IDR, there is a larger share of institutionally and nationally collaborated publications. The result implies that institutional and national collaboration play a more important role for IDR compared to their overall contribution to research. One plausible reason is that the setup of IDR centres in universities and countries encourages researchers from multiple disciplines but within the same university or country to collaborate with one another.

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Figure 3.2— *Share of publications in each collaboration type out of publications with an IDR score and out of publications that belong to the top 10% IDR; all divisions; for the UK; 2009-2013.*

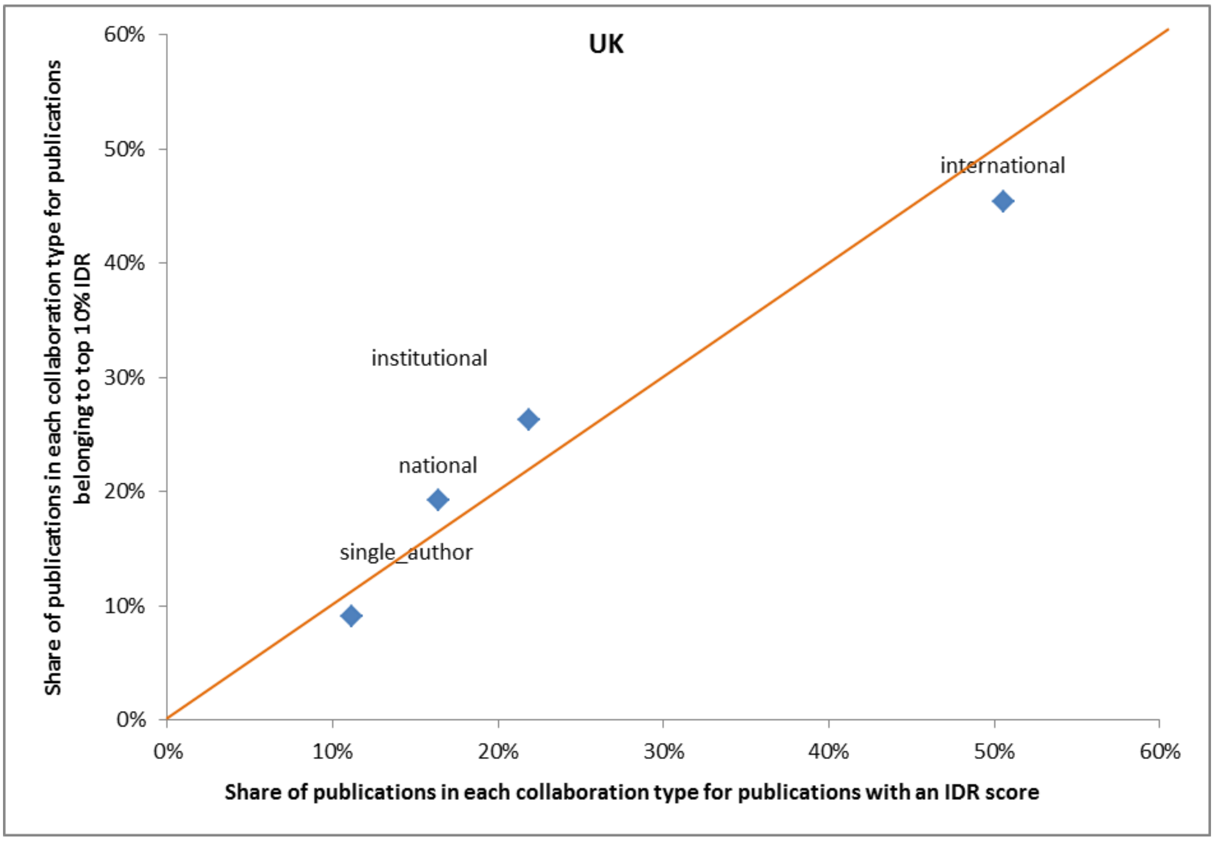

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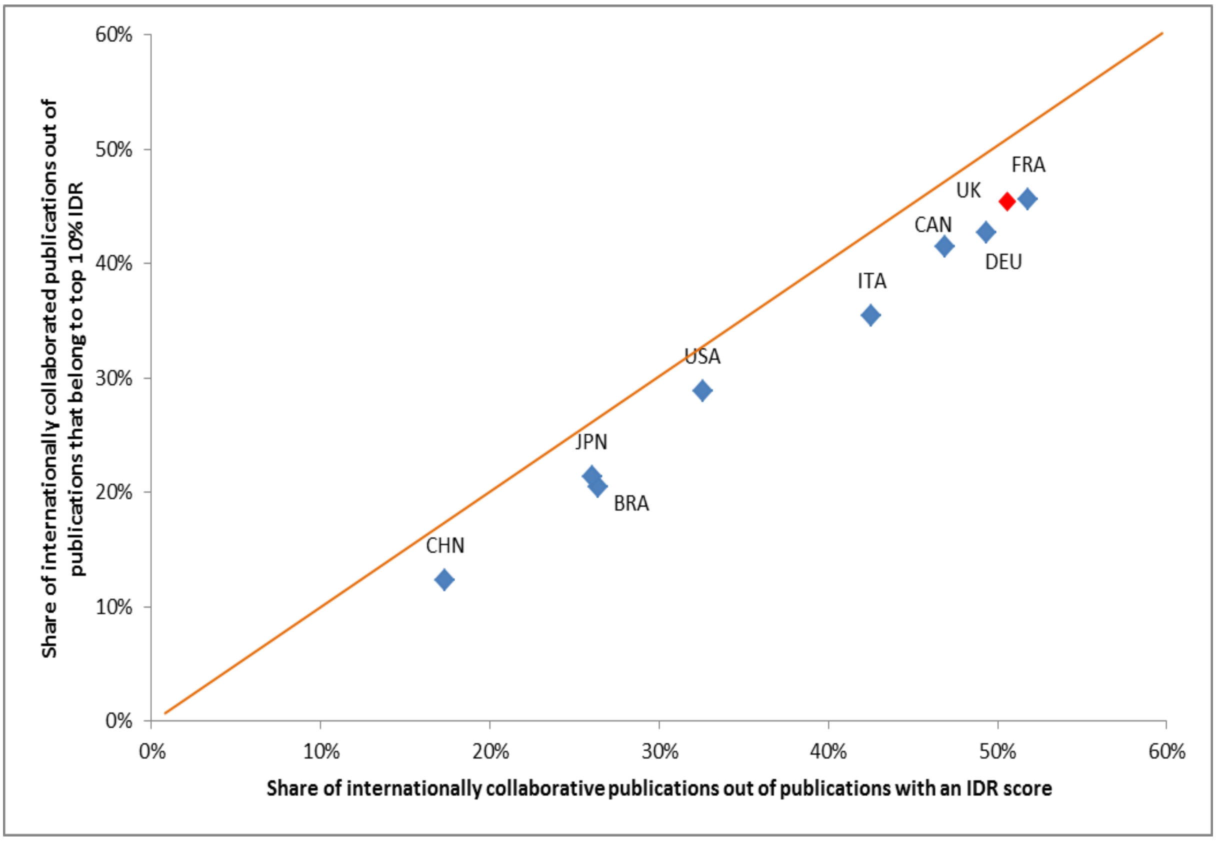
Figure 3.3— *Share of internationally collaborative publications out of publications with an IDR score and out of publications that belong to the top 10% IDR; all divisions; per country; 2009-2013.*



71. International collaboration is often associated with higher citation impact because collaborative publications are more likely to have higher exposure to a wider research community and therefore are more frequently cited. Figure 3.5 corroborates this, showing that for all comparator countries the FWCI of their internationally collaborative publications is above 1.5 (much higher than the numbers in Figure 2.1).

72. However, IDR is not associated with higher citation impact for internationally collaborative publications, in line with the finding in Figure 2.1. It is clear from Figure 3.5 that, for all comparator countries , the FWCI of internationally collaborative publications of all publications with an IDR score is always higher than that of international collaborative publications belonging to the top 10% IDR.

73. In fact, for the UK, across all four collaboration types the FWCI of publications belonging to the top 10% IDR is always lower than that of all publications with an IDR score (Figure 3.4). The

result confirms what we found in Chapter 2; IDR is associated with lower citation impact. This conclusion holds for all geographical collaboration types.

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Figure 3.4— *FWCI of publications in each collaboration type for publications with an IDR score and for publications that belong to the top 10% IDR; all divisions; for the UK; 2009-2013.*

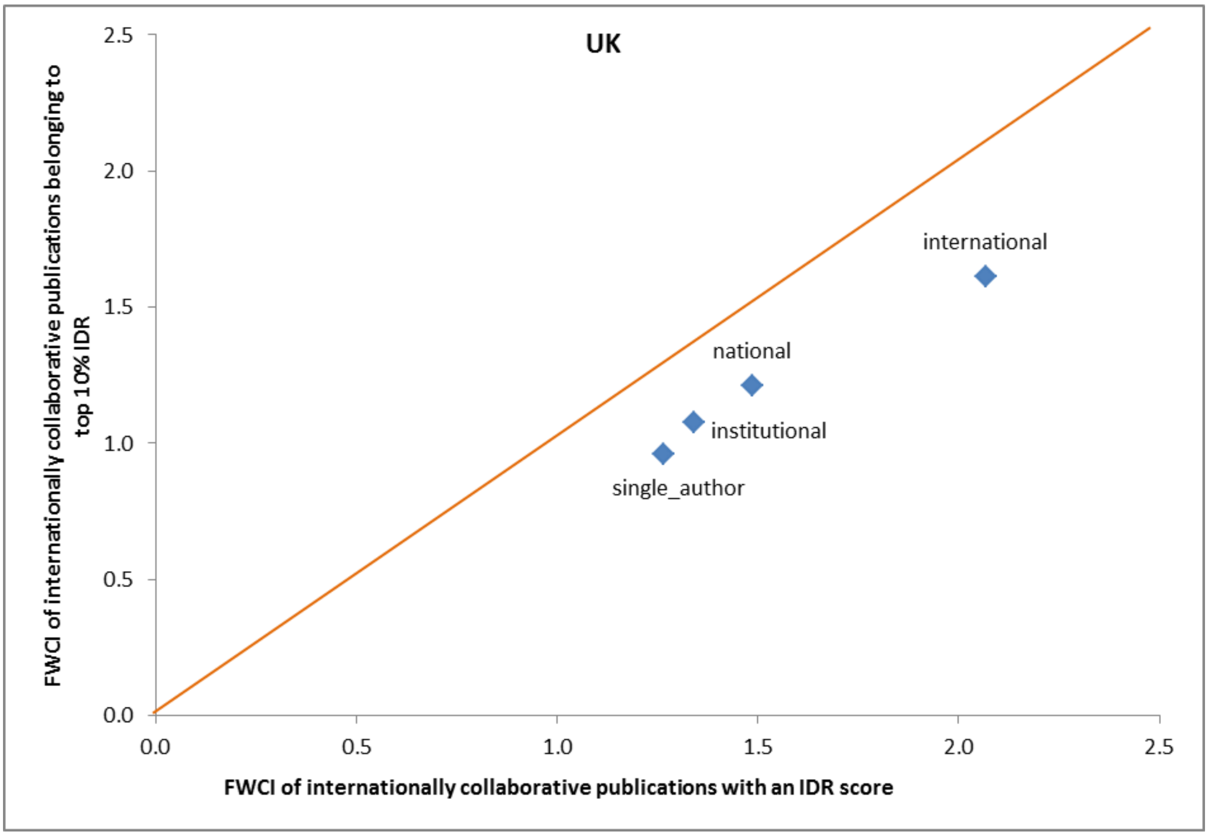

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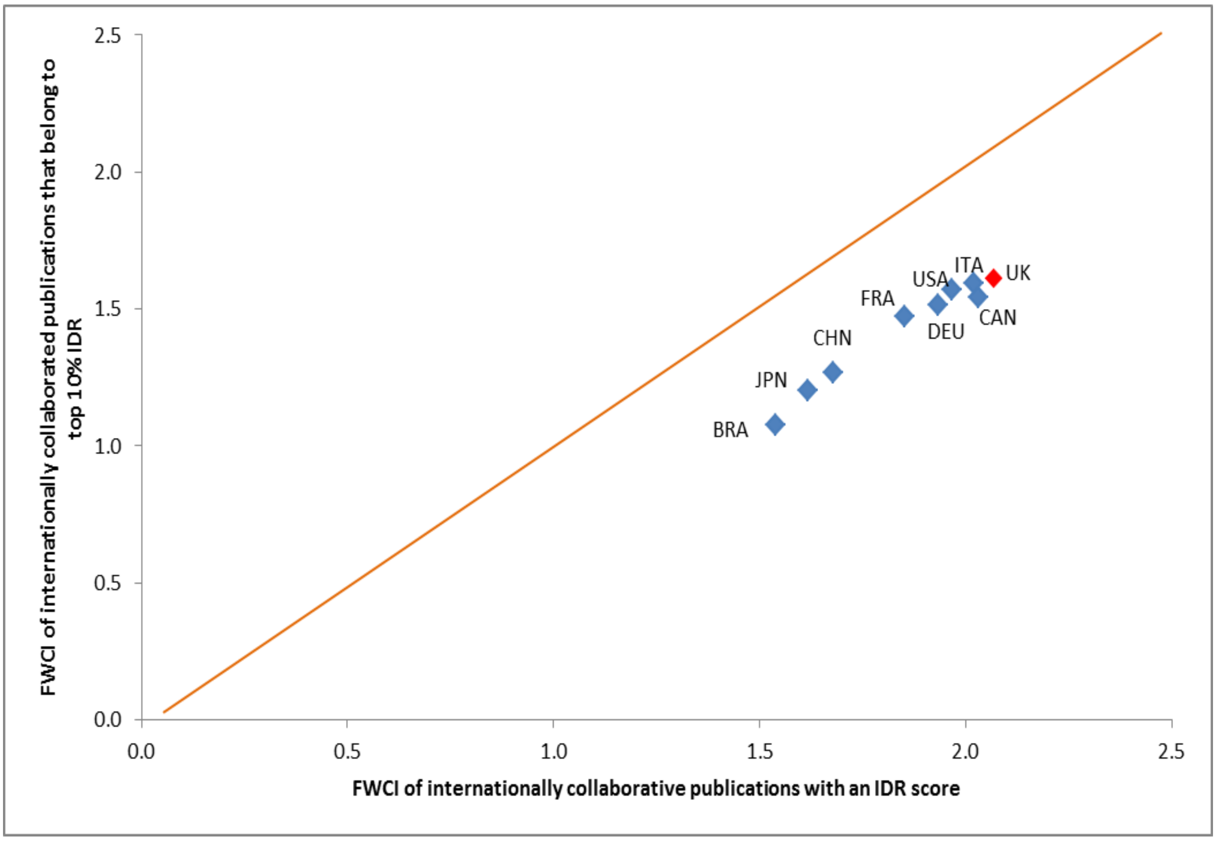
Figure 3.5— *FWCI of internationally collaborative publications for publications with an IDR score and for publications that belong to the top 10% IDR; all divisions; per country; 2009-2013.*



3.4 Whether IDR is associated with collaboration with the corporate sector varies across countries

74. The connection between academia and industry is an important aspect of research performance. There have been studies investigating the implications and benefits of academic and commercially oriented research and the complementarity between the two sectors.[39] Co-authored publications across sectors are one measure of such collaboration. Here we define co-authored publications as those with at least one author from academia and at least one author from the corporate sector.

75. Is a higher share of IDR publications associated with higher levels of collaboration with the corporate sector? The literature seems to suggest such a correlation: Van Rijnsoever and Hessels (2011)[40], and Carayol and Thi (2005)[41] found that IDR practices are associated with the intensity of academic-corporate collaboration. Our results (see Figure 3.6) however show that the effect differs by country. Among the comparator countries, Germany and Japan's publications in top 10% IDR have a higher share of publications that are academic-corporate collaborations (although the difference is only significant for Germany), while we found the opposite result for the rest of the countries, including the UK. This suggests that contextual differences across countries lead to disparate results.

76. The level of collaboration with government is lower in publications belonging to the top 10% IDR than in the overall

[39] Larsen, Maria Theresa (2011). The implications of academic enterprise for public science: An overview of the empirical evidence. *Research Policy*, 40(1) pp. 6-19. doi:10.1016/j.respol.2010.09.013.
[40] Van Rijnsoever, F. J., and Hessels, L. K. (2011). Factors associated with disciplinary and interdisciplinary research collaboration, *Research Policy* 40(3), 463-472.
[41] Carayol, N., and Thi, T. U. N. (2005). Why do academic scientists engage in interdisciplinary research? *Research Evaluation* 14(1), 70-79.

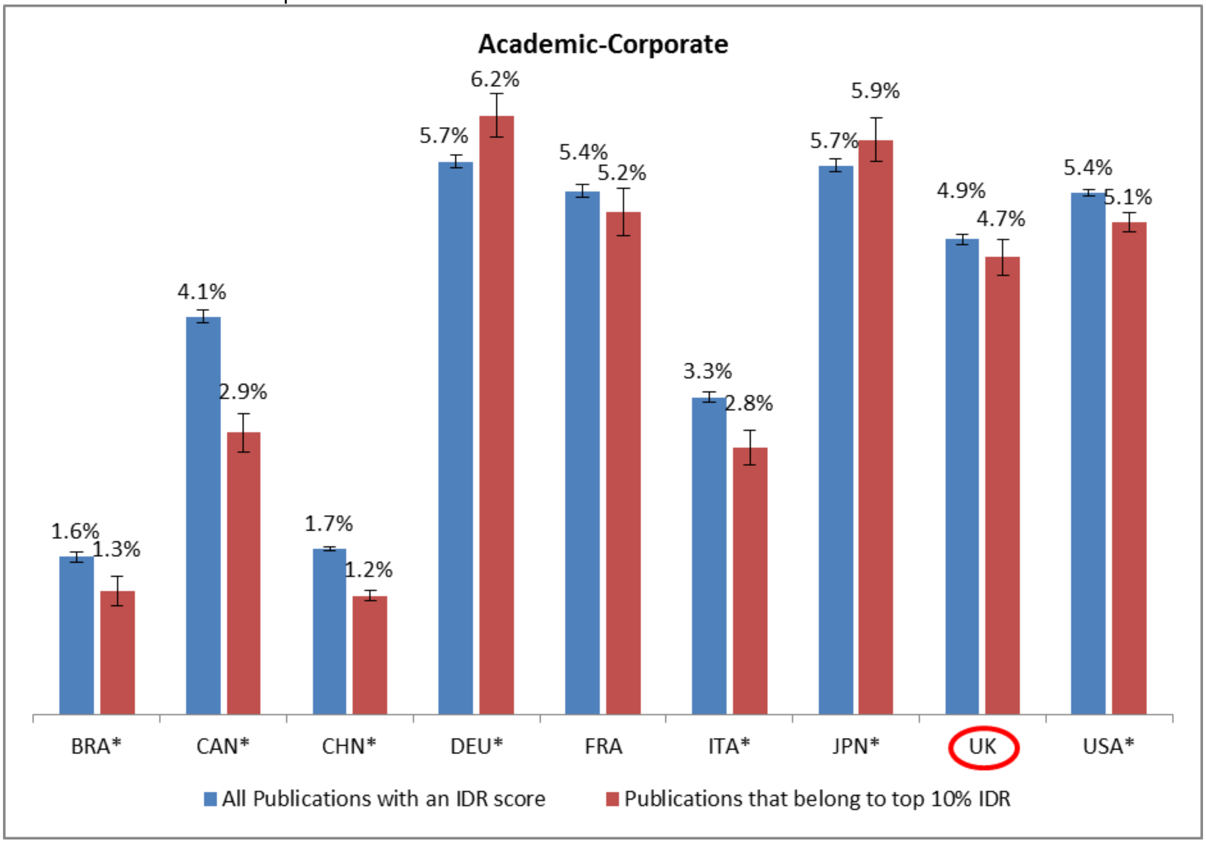
publications. In terms of collaboration with the medical sector, we see the opposite effect. Except for Italy, Brazil, and Japan, the level of collaboration with the medical sector is higher in publications belonging to the top 10% IDR compared to all publications with an IDR score. This further confirms what we found in Table 1.1: for the UK, the top 20 organizations with the highest share of publications in the top 10% IDR include a good number of hospitals.

77. Figure 3.7 takes a closer look at academic-corporate collaborative publications for UK publications that belong to the top 10% IDR. We can see that collaboration with the corporate sector occurs more frequently in the Chemical Sciences, the Biological Sciences, and Technology.

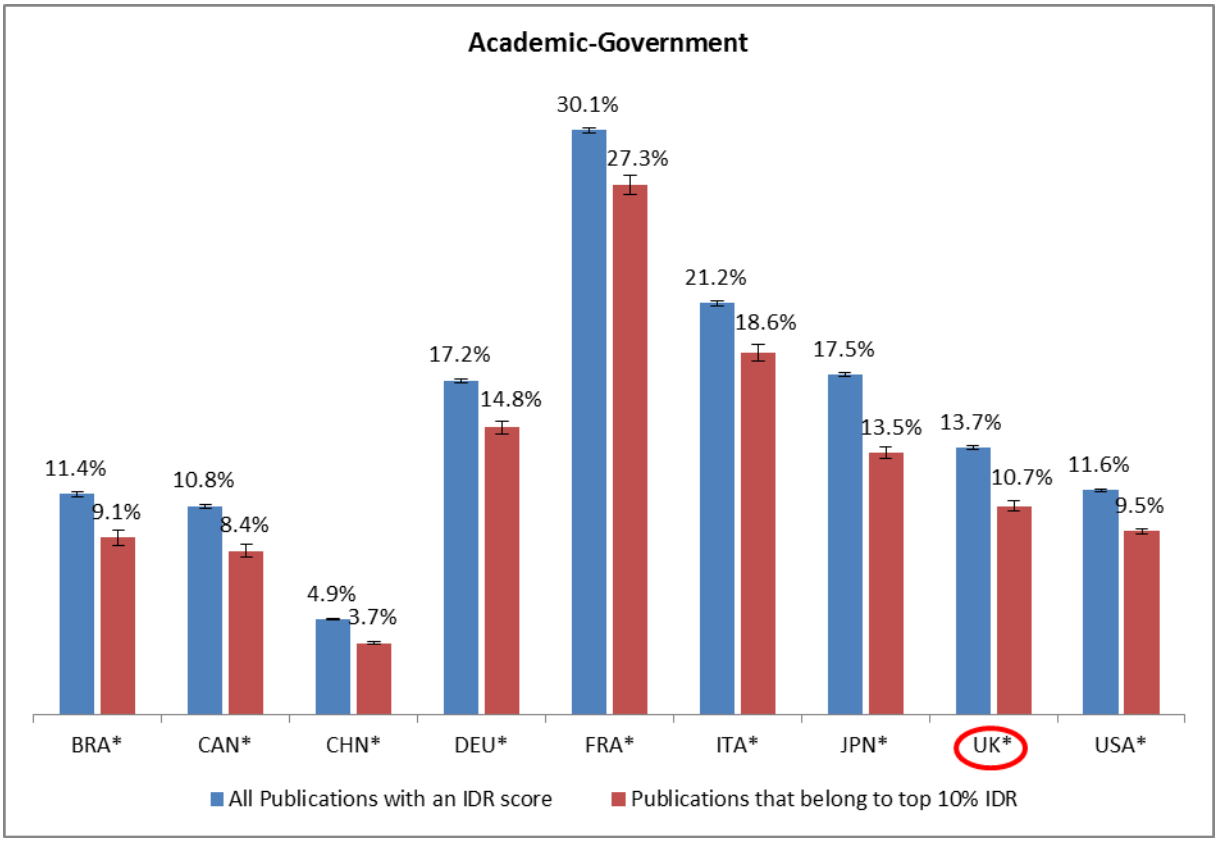
+

Figure 3.6— *Share of cross-sector collaborative publications out of publications with an IDR score and out of publications that belong to the top 10% IDR; all divisions; per country; 2009-2013. Error bars show the Wald 95% confidence intervals and the stars indicate a significant change (at the 5% significance level) between the percentage on the blue bar and that on the red bar using the Binomial Proportion Test.*

a. Academic-corporate



b. Academic-government



c. Academic-Medical

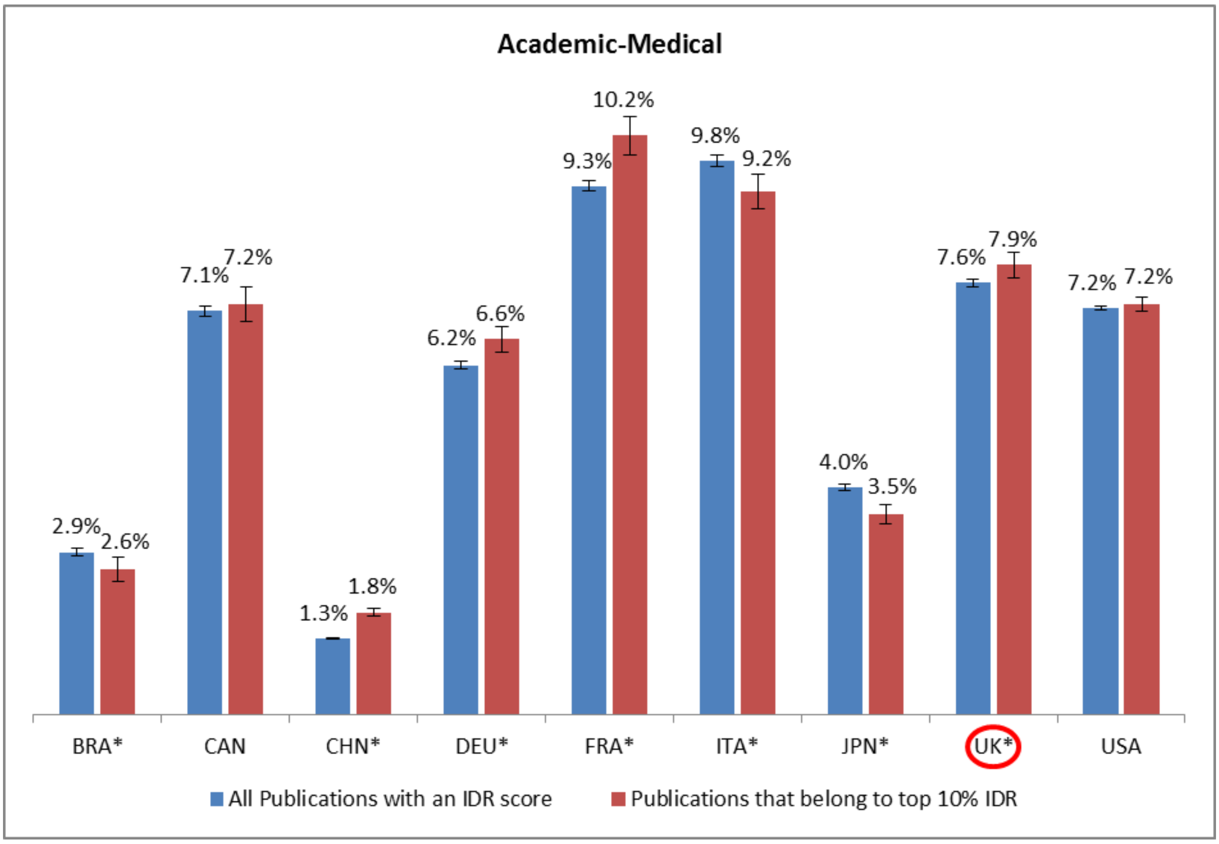


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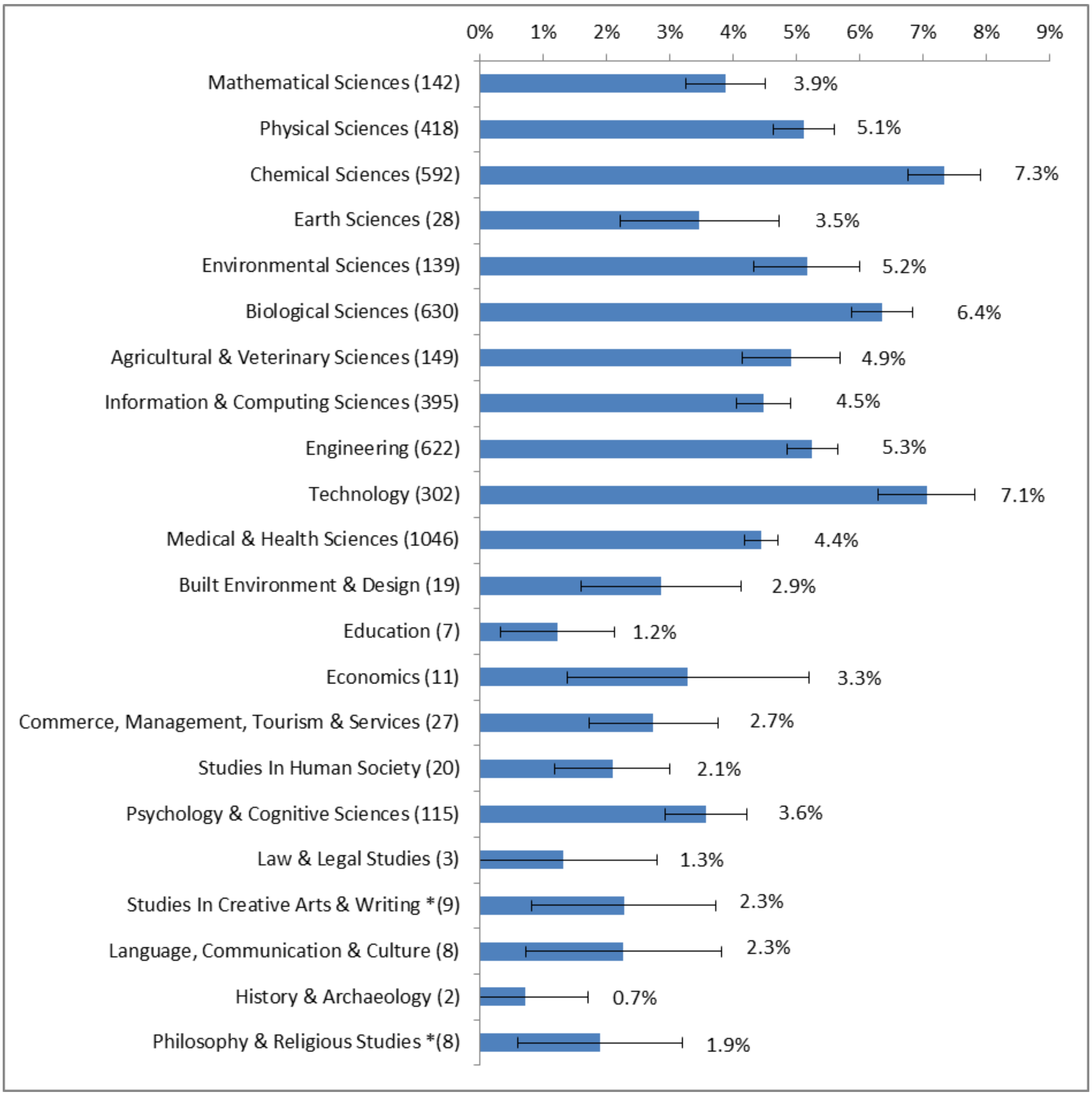
Figure 3.7— *Share of academic-corporate collaborative publications out of publications that belong to the top 10% IDR; per division; for the UK; 2009 and 2013. Error bars show the Wald 95% confidence intervals and the stars indicate a significant change (at the 5% significance level) from 2009 to 2013 using the Binomial Proportion Test. The numbers in the brackets are the number of academic-corporate collaborative publications.*



Chapter 4
Conclusion

This chapter summarizes the key findings and concludes.

4.1 Conclusions

78. We employ a novel approach that infers whether an article is interdisciplinary from that article's bibliography references. Articles with references that are "far away" from each other in terms of their subjects and topics are considered more interdisciplinary. Our approach does not depend on any pre-defined subject classifications and is able to capture the dynamics of the research landscape in which subjects are emerging and changing over time.

79. Our results show three main conclusions:
    - ► Emerging countries such as China and Brazil have a higher share of interdisciplinary research (IDR) publications out of their research output.
    - ► IDR is associated with lower citation impact overall, but a higher level of citations in patent applications.
    - ► IDR is correlated to a lower level of international collaboration, but its relation with the collaboration with industry depends on the contextual situation of each country.

80. Further research is needed to investigate the reasons behind these findings. Understanding these reasons will be important for designing programmes and policies for IDR. Furthermore, as recommended in the UK's Triennial Review of the Research Councils,[42] it is necessary for funding bodies and research councils to investigate the extent to which the concerns over IDR are a real or a perceived problem and to ensure disciplinary boundaries do not inhibit the funding of IDR.

[42] Available at http://www.rcuk.ac.uk/media/news/140416/

Appendix A
Methodology for Classifying Articles as Interdisciplinary

An essential step in this study is to define IDR in the context of bibliometric studies, which requires classifying individual articles as IDR or single-discipline. A good method needs to address the following questions:

- ► What makes an article interdisciplinary? Which characteristics does an interdisciplinary article typically have?
- ► How can the definition of disciplines evolve over time to reflect the dynamics of research?

Many methods have been used in the bibliometric literature to define IDR. The *Handbook of Quantitative Science and Technology Research*[43] has a brief discussion on these methods including collaboration amongst authors from different disciplines, co-occurrence of several classification codes in publications, interdisciplinary nature of publication journals, and cross-disciplinary references and citations. Cross-disciplinary references and citations that rely on the journal classification of an article's references and citations is the most frequently used method.[44]

The main drawback of the above mentioned methods is their reliance on existing subject classification schemes, in most of the cases journal classification schemes. One problem with this is that journal classification schemes require stability and therefore do not always reflect new developments in areas of research. Similarly, the rigidness of such a classification

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43 http://download.springer.com/static/pdf/550/chp%253A10.1007%252F1-4020-2755-9_20.pdf?auth66=1421941802_6bb34ced7cf3edc25334f781ee2ba200&ext=.pdf

44 Two examples using this method are available at https://greekuniversityreform.files.wordpress.com/2008/03/reinterdisc.pdf and http://www.informationr.net/ir/9-4/paper182.html.

system does not allow for subtle differences between disciplines. A publication in a discipline that is relatively small in size, citing a publication that is in the nearest adjacent discipline makes this article multidisciplinary. If a publication is in a larger discipline, citing a publication that is still within the discipline but on nearly unrelated topics would make this publication monodisciplinary. One could question whether this level of arbitrariness is suitable when studying the phenomenon of IDR.

To address these drawbacks, Elsevier proposes a fully flexible approach, with the following central principle: If an article references articles that are relatively "far" from each other, it is an indication of interdisciplinarity. If the journals are "close", we class the references as being "close".

The notions of 'far' and 'close' are described in more detail below. The strength of this approach is that it does not rely on rigid journal classifications when defining IDR publications, but instead uses information at the publication level. Our proposed approach consists of two steps:

Step 1: mapping journals

We create a journal similarity index that is based on the co-occurrences of two journals in articles' references. The more often they occur together, the higher the similarity level between these two journals.[45] Multi-disciplinary journals such as Nature are excluded in this step because articles in these journals cite papers from journals of many different research fields and therefore will always be placed in the centre of the map. Classification of articles in these journals will be addressed in Step 2.

Consider a simple example with only three journals (Table A.1). Journal A has two articles: A1 and A2. Article A1 cites Articles A2 and B1, and Article A2 cites B2 and B3. Similarly, Journal B has three articles and Journal C has five.

[45] This approach is discussed in Hansen, L., and Leydesdorff. Mapping interdisciplinarity at the interfaces between the Science Citation Index and the Social Science Citation Index. *Scientometrics*, 71 (2007), pp. 391–40.

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Table A.1— *An example with three journals, their articles and references.*

Journals	Articles	References
Journal A	A1	A2, B1
	A2	B2, B3
Journal B	B1	A1, A2
	B2	B1, B3
	B3	A1, B1
Journal C	C1	C2, C4,
	C2	C1, C4,
	C3	C1, C2, C4,
	C4	A1, C1, C2
	C5	C1, C2

We can create a journal co-occurrence matrix based on the information above where the numbers indicate the number of co-occurrences of the journals (Table A.2).

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Table A.2— *Co-occurrence of journals in the simple example.*

	Journal A	Journal B	Journal C
Journal A	1[46]	2[47]	1
Journal B	2	2	0
Journal C	1	0	5

We can see that Journal A and Journal B co-occur twice and Journal A and Journal C co-occur once. Note that in this step if one journal appears multiple times in one article's references we only count it once. We need to consider that since Journal C occurs more often than Journal A and B in references, the probability that Journal C co-occurs with other journals is also higher than Journal A and B. To normalize for this, pointwise mutual information is computed (PMI):

$$PMI(A;B) = \log\left(\frac{p(A,B)}{p(A)p(B)}\right),$$

where $p(A,B)$ denotes the probability that Journal A and B co-occur, $p(A)$ and $p(B)$ denote the probability that Journal A and Journal B occur individually in references, respectively. PMI therefore tells how much the actual probability of a particular co-occurrence of events differs from what we would expect on

[46] Journal A only appears twice (co-occurred once) on Article B1.
[47] Journal A and B co-occur on Article A1 and B3.

the basis of the probabilities of the individual events and with the assumption of independence.

In our example, $p(A, B)$ is equal to 2 divided by 10 because Journals A and B co-occur twice (in Articles A1 and B3) and there are 10 articles in total. Similarly, $p(A)$ is equal to 4 divided by 10 because Journal A appears in 4 out of the 10 references. The PMI for journal A and B is equal to $\log\left(\frac{2/10}{4/10*4/10}\right)$.

We further normalize PMI to limit it between -1 and 1 by applying the following formula to calculate normalized pointwise mutual information (NPMI):

$$NPMI(A; B) = \frac{PMI(A; B)}{-\log[(p(A, B)]}.$$

NPMI equals −1 for journals that never occur together and 1 for complete co-occurrences. In our context, journals co-occurring often are likely to be in the same subject area, and journals from different disciplines are expected to have lower mutual information. For our example, the NPMI between journal pairs is calculated in Table A.3.

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Table A.3— *NPMI between journal pairs.*

	Journal A	**Journal B**	**Journal C**
Journal A	-0.20[48]	0.14	-0.30
Journal B	0.14	0.14	-1
Journal C	-0.30	-1	1

This means that Journals A and B are likely to be in closely related subject areas and Journal C probably belongs to a "far away" subject area.

Ideally the journal map needs to be constructed by year considering that the landscape of science is changing over time: two journals that are "far" from each other in 2009 may become closer in 2013. The drawback of constructing the map year by year is that for a subset of journals the number of co-

[48] The low score is due to the construction of this artificial example. In real cases, articles from the same journal are often co-cited so NPMI of the same journal is always high.

occurrences is small because the number of occurrences of these journals in articles is also small. A journal map based on these small numbers is likely to be unreliable. We therefore also constructed one journal map using the five-year data (2009-2013). We then compare the NPMIs from the two ways of constructing the journal map – one using only 2009 data and one using 2009-2013 data. The Spearman correlation coefficient of the two lists of NPMIs is equal to 0.9. We therefore conclude that the journal map depends little on the time period used, and so constructed one journal map for the five-year period for robustness. This map is used throughout this study.

In this journal map, examples of "close" journals are in Table A.4.

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Table A.4— *"Close" journals.*

Journal 1	Journal 2
Review of Contemporary Philosophy	Contemporary Readings in Law and Social Justice
International Endodontic Journal	Journal of Endodontics
Advanced Studies in Contemporary Mathematics (Kyungshang)	Proceedings of the Jangjeon Mathematical Society
Clinical Oral Implants Research	International Journal of Oral and Maxillofacial Implants
Nuclear Physics A	Physical Review C - Nuclear Physics
International Journal of Leprosy and Other Mycobacterial Diseases	Leprosy Review
Journal of Glaciology	Annals of Glaciology
Energy Education Science and Technology Part B: Social and Educational Studies	Energy Education Science and Technology Part A: Energy Science and Research
Sport Psychologist	Journal of Applied Sport Psychology
International Journal of Primatology	American Journal of Primatology
World Heart Journal	Open Nutraceuticals Journal
Angle Orthodontist	European Journal of Orthodontics
Journal of Bryology	Cryptogamie, Bryologie
Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics	Physical Review D - Particles, Fields, Gravitation and Cosmology
Music Theory Spectrum	Journal of Music Theory
Operative Dentistry	Journal of Adhesive Dentistry
Indian Journal of Leprosy	Leprosy Review
Revue de Qumran	Dead Sea Discoveries

Bulletin of Volcanology	Journal of Volcanology and Geothermal Research
Journal of Clinical Periodontology	Journal of Periodontology

We can see that in most of the cases each pair of journals is from a very specific research area, confirming that these are very "close" journals.

Examples of "far away" journals are in Table A.5.

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Table A.5— *"Far away" journals.*

Journal 1	Journal 2
Archives of Internal Medicine	Journal of Applied Physics
New England Journal of Medicine	Physical Review D - Particles, Fields, Gravitation and Cosmology
Lancet, The	Physical Review A - Atomic, Molecular, and Optical Physics
JAMA - Journal of the American Medical Association	Physical Review D - Particles, Fields, Gravitation and Cosmology
Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics	JAMA - Journal of the American Medical Association
Lancet, The	Physical Review D - Particles, Fields, Gravitation and Cosmology
American Journal of Public Health	Journal of Applied Physics
Physical Review A - Atomic, Molecular, and Optical Physics	JAMA - Journal of the American Medical Association
Applied Physics Letters	Journal of the American Geriatrics Society
New England Journal of Medicine	IEEE Transactions on Communications
Circulation	Physical Review D - Particles, Fields, Gravitation and Cosmology
Lancet, The	Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics
Annals of Internal Medicine	Journal of Applied Physics
Applied Physics Letters	Cochrane Database of Systematic Reviews
Applied Physics Letters	American Journal of Preventive Medicine
Applied Physics Letters	British Medical Journal
BMC Public Health	Applied Physics Letters
New England Journal of Medicine	Physical Review A - Atomic, Molecular, and Optical Physics
British Medical Journal	Physical Review D - Particles, Fields, Gravitation and Cosmology
New England Journal of Medicine	Journal of High Energy Physics

What occurs very often in this table is that one journal is a Physics journal and the other is a Medicine journal. Again this confirms that the "far away" journals we found are from different subject areas.[49]

Step 2: Calculate the IDR score for each article

Now we take an Article X that cites Articles A1, A2 and B2. These three references are published in Journal A and Journal B. For this article we calculate a score which equals the weighted average of the NPMIs:

$$IDR\ score(X) = \frac{2*NPMI(A;B)+1*NPMI(A;A)}{3} = 0.02.$$

The weights are given in this way: if Journal A appears *n* times and Journal B appears *k* times on the article's reference list, the weights for $NPMI(A;B)$, $NPMI(A;A), NPMI(B;B)$ is $n*k$, $n(n-1)/2$, and $k(k-1)/2$, respectively.

We take another Article Y that cites A1, B1, C1 and C2. The IDR score for this article is

$$IDR\ score(Y) = \frac{1*NPMI(A;B)+2*NPMI(A;C)+2*NPMI(B;C)+1*NPMI(C;C)}{6} = -0.24.$$

Article Y has a much lower score than Article X and therefore is more likely to be an IDR article. This is because Article Y cites articles from three different journals and journal C is considered to be in a very different discipline than Journal A and B in Step 1.

Since only the information on the publishing journals of the references of the article (instead of the publishing journal of the article itself) is used, articles in multidisciplinary journals such as Nature and Science can be addressed in the same way in this step to get an IDR score.

There are around 11.2 million publications (i.e., articles, reviews and conference proceedings) covered by Scopus in the period 2009-2013. Among these publications, 1.5 million do not have any references. Out of the remaining 9.7 million

[49] We only give examples of journal pairs that have been cited together at least once in articles in 2009-2013 (NPMI>-1). This is why the combination of, for example, one Social Science journal and one Physics journal does not appear in the table. Since they are never cited together, they have a NPMI equal to -1.

publications we obtain an IDR score for 8.7 million[50]. This results in a total coverage of 78%. This study is based on these 8.7 million publications with an IDR score.

Figures A.1 and A.2 are histograms that show the distribution of the IDR scores for Scopus publications in 2009-2013 for the world and the UK, respectively. We see that only a small percentage of the publications have an IDR score lower than zero (very interdisciplinary). The majority of the articles concentrate in the range between 0.2 and 0.4.

[50] The reason that some publications do not obtain a score is that the publishing journals of their references are not covered in Scopus. For robustness, we also exclude publications for which less than three references are found in Scopus.

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Figure A.1— *The distribution of IDR scores; all divisions; for the world; 2009-2013.*

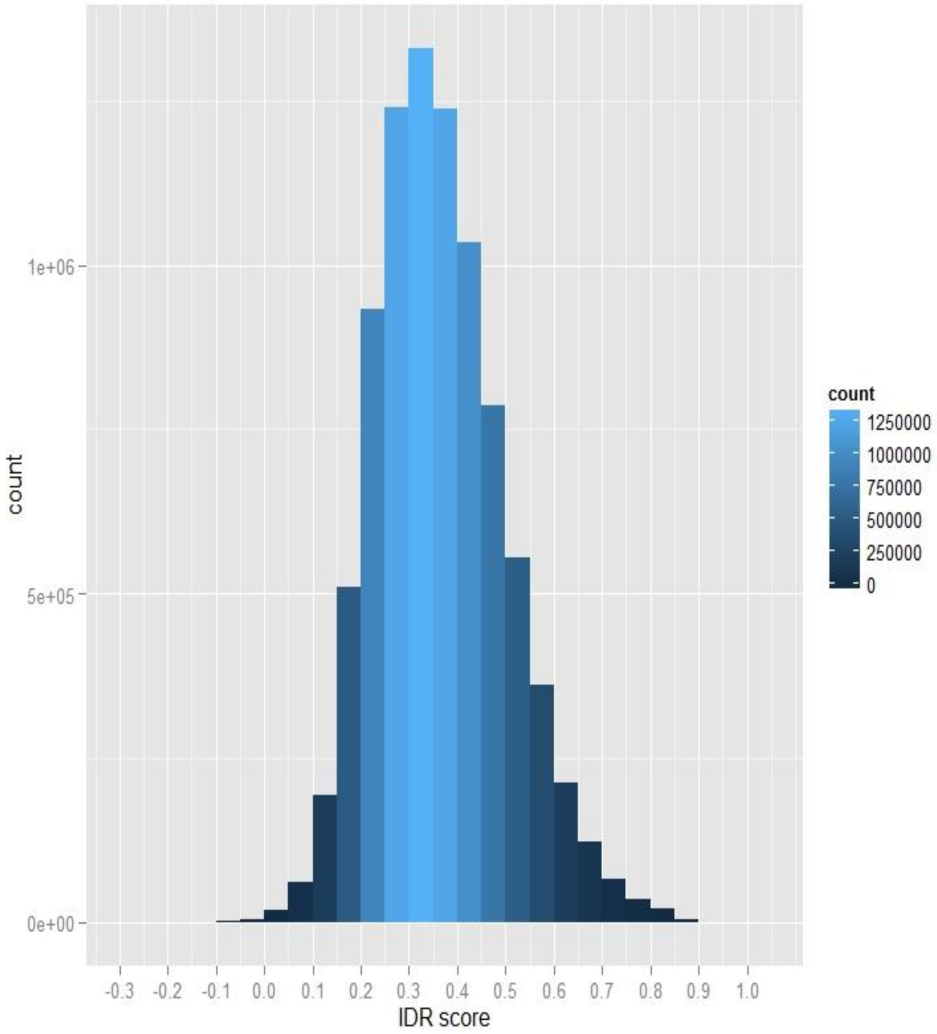

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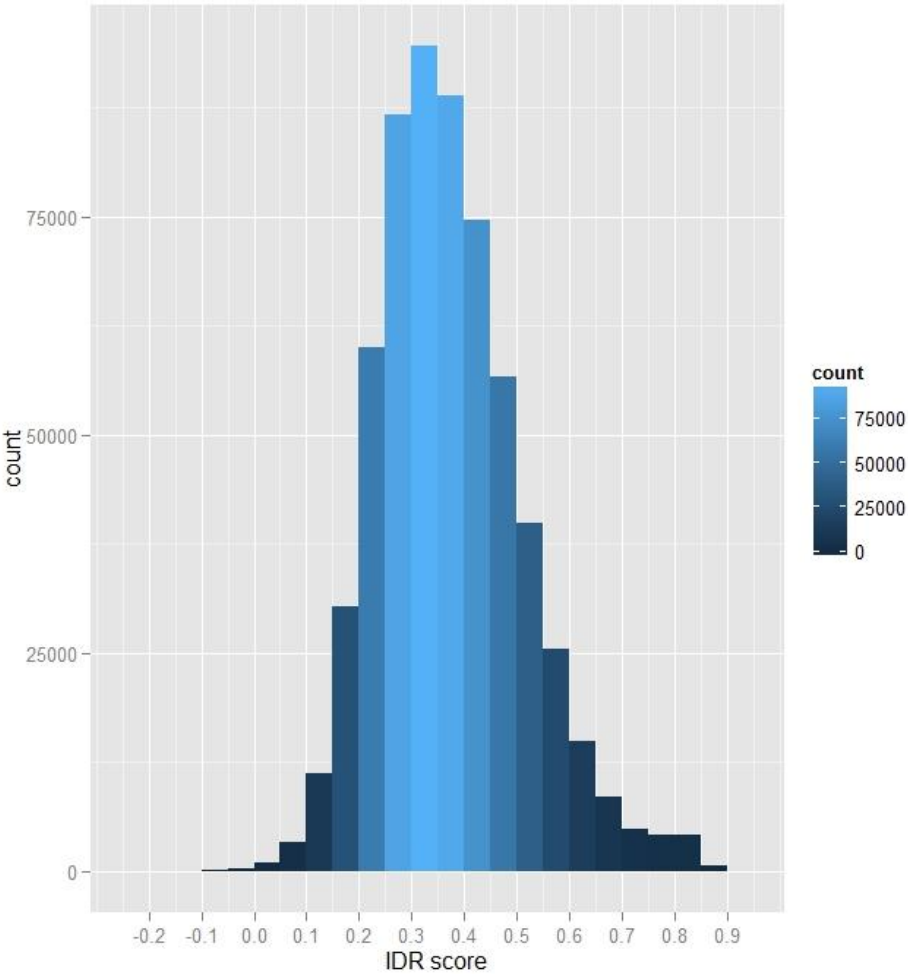
Figure A.2— *The distribution of IDR scores; all divisions; for the UK; 2009-2013.*



Figures A.3 and A.4 show the percentages of Scopus publications with an IDR score for the world and for the UK, respectively. We see that in general the percentages are high for divisions in the Natural Sciences and the Social Sciences, and lower for divisions in the Humanities. The percentages are also in general higher for the UK than for the world.

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Figure A.3— *Percentage of Scopus publications with an IDR score; per division; for the world; 2009-2013.*

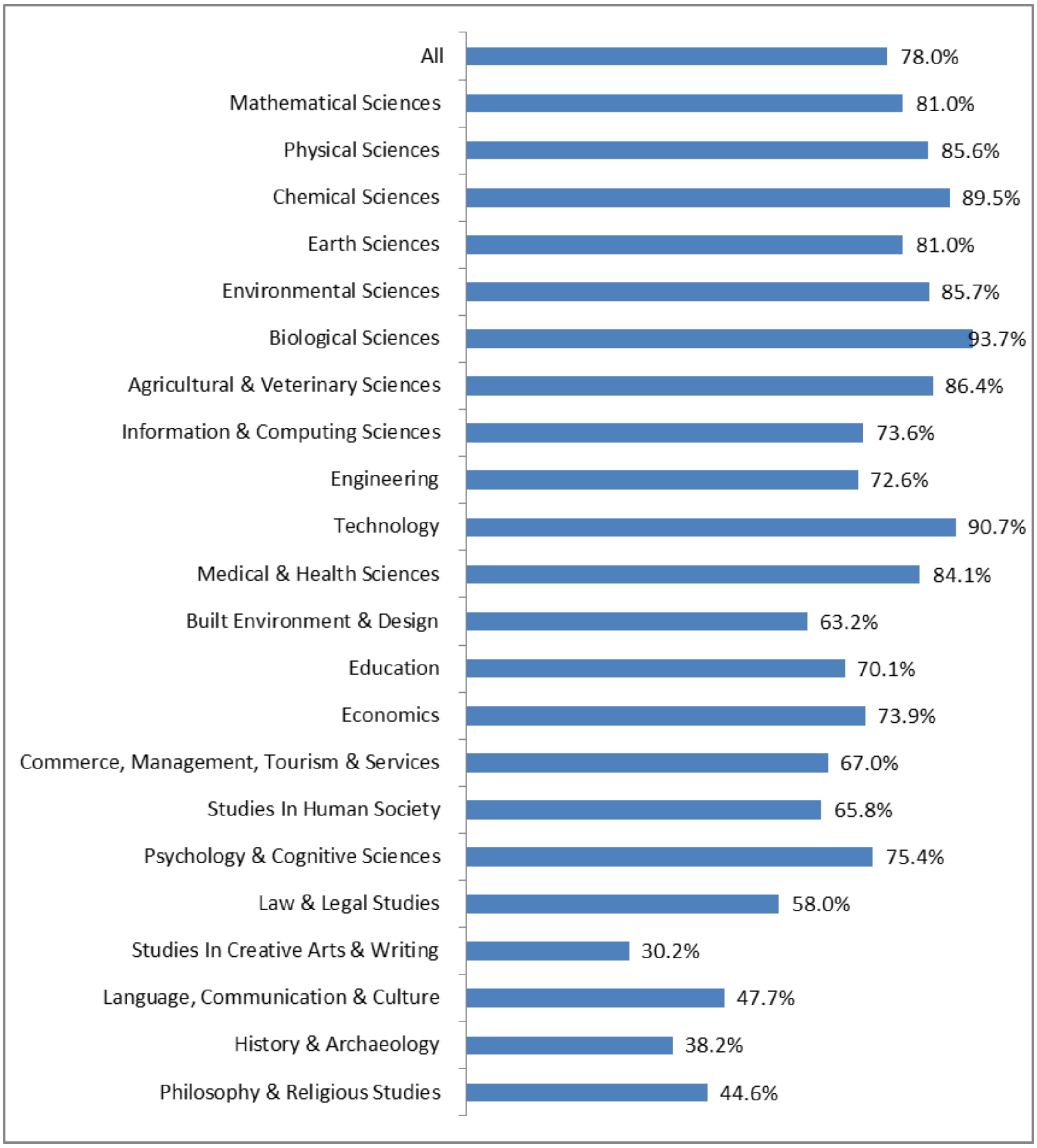

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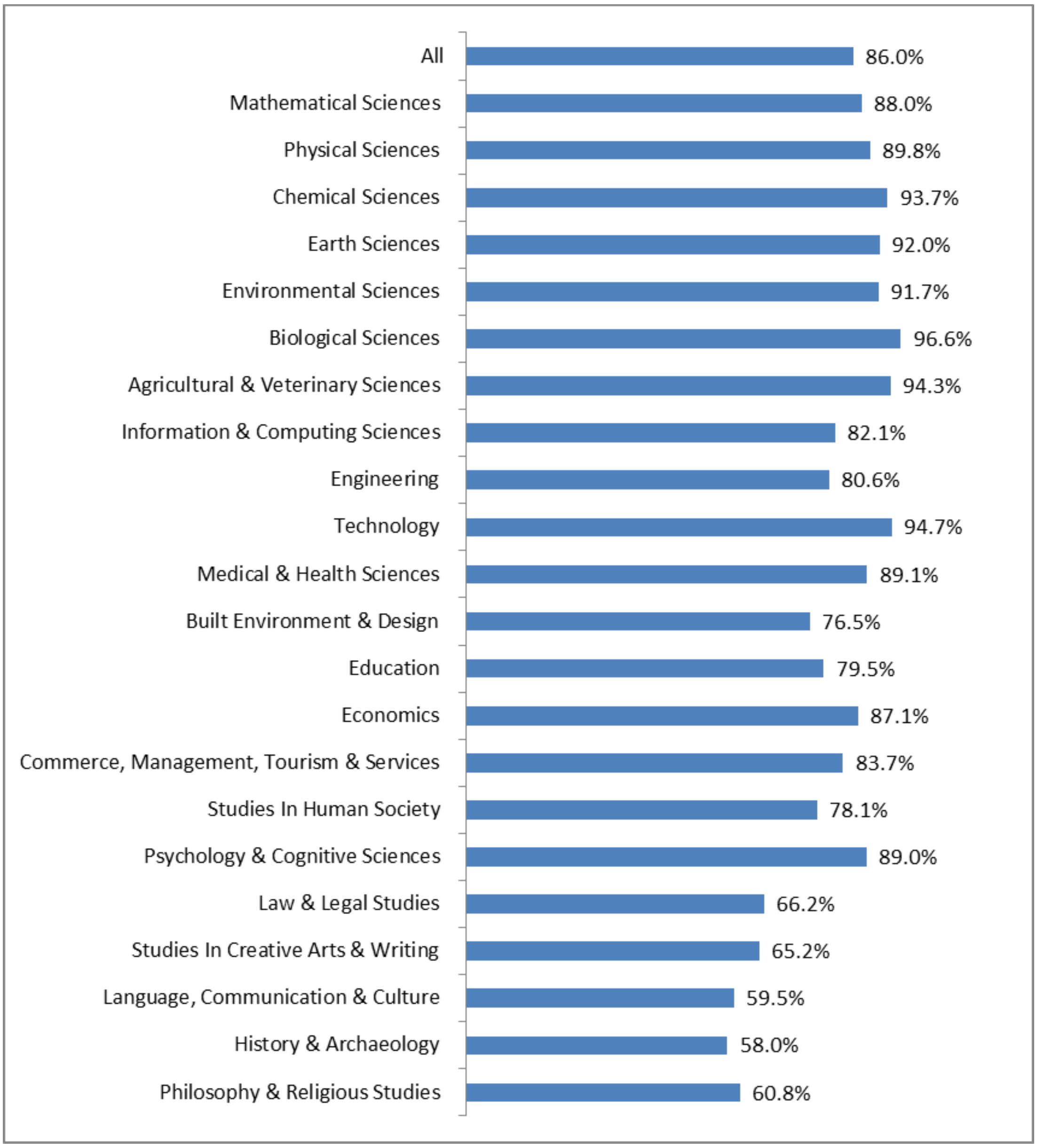
Figure A.4— *Percentage of Scopus publications with an IDR score; per division; for the UK; 2009-2013.*



The percentage also differs by country (Figure A.5). It is the highest for Canada, Italy and the UK and the lowest for China.

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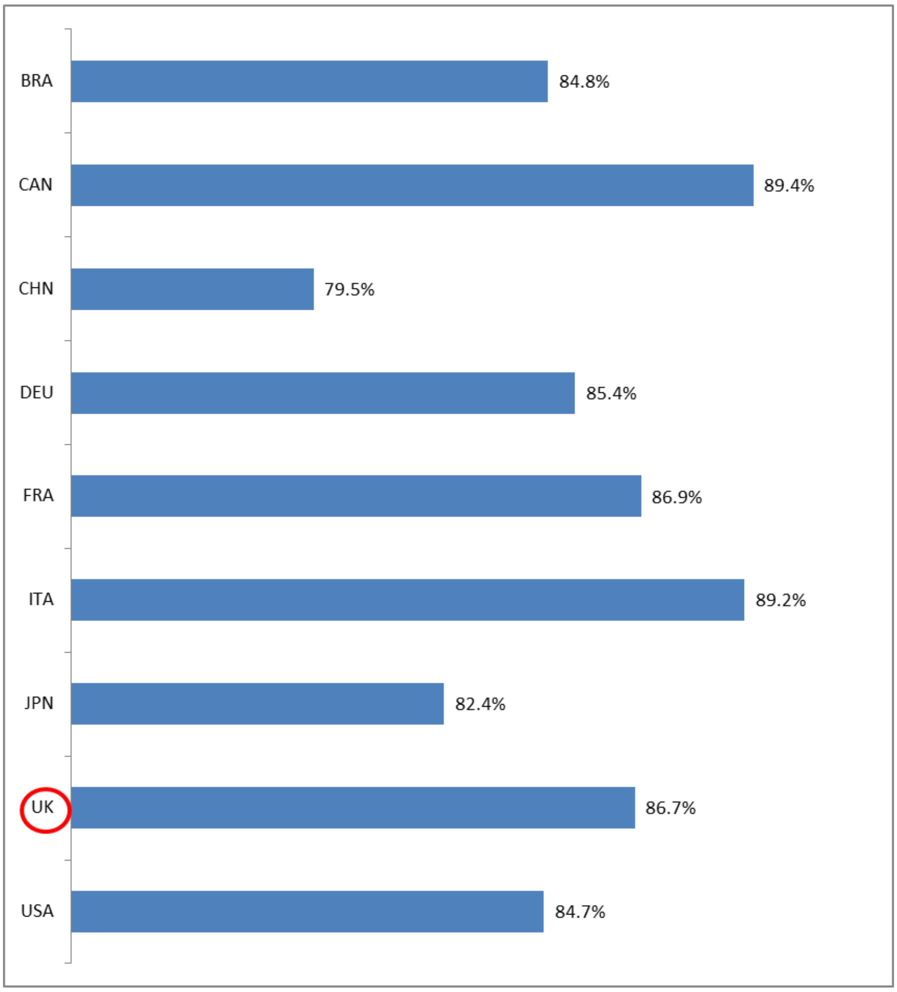
Figure A.5— *Percentage of Scopus publications with an IDR score; all divisions; per country; 2009-2013.*



Appendix B
Mapping between Scopus Subject Areas and ANZSRC Groups

Mapping between Scopus detailed subject areas and ANZSRC groups and a list of unmatched groups are in the attached file named "Mapping.xlsx".

Appendix C
Mapping between Research Domains and ANZSRC Divisions

Research domains	ANZSRC divisions
Natural Sciences	Mathematical Sciences
	Physical Sciences
	Chemical Sciences
	Earth Sciences
	Environmental Sciences
	Biological Sciences
	Agricultural & Veterinary Sciences
Engineering & Technology	Information & Computing Sciences
	Engineering
	Technology
	Built Environment & Design
Health Sciences	Medical & Health Sciences
Social Sciences	Education
	Economics
	Commerce, Management, Tourism & Services
	Studies In Human Society
	Psychology & Cognitive Sciences
	Law & Legal Studies
Humanities	Studies In Creative Arts & Writing
	Language, Communication & Culture
	History & Archaeology
	Philosophy & Religious Studies

Appendix D
List of Abbreviations

Full name	Abbreviation
Australian and New Zealand Standard Research Classification	ANZSRC
Field-weighted citation impact	FWCI
Field-weighted download impact	FWDI
Interdisciplinary research	IDR
Medical Research Council	MRC
Normalized pointwise mutual information	NPMI
Pointwise mutual information	PMI
Research Excellence Framework	REF

Authors

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Notes

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