Interdisciplinary research: methodologies for identification and assessment

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Report on interdisciplinary research: methodologies for identification and assessment

This project was commissioned by the Medical Research Council (MRC) and informed by a steering group that included Research Councils UK (RCUK), the Higher Education Funding Council for England (HEFCE) and expert advisors Professor Michael Hopkins (SPRU, University of Sussex) and Professor Ismael Rafols (INGENIO, Universitat Politecnica de Valencia).

The objective of the study behind this report was to compare the consistency of indicators of ‘interdisciplinarity’ and to identify a preferred methodology. The outcomes reveal that choice of data, methodology and indicators can produce seriously inconsistent results despite a common set of disciplines and countries. This raises questions about how interdisciplinarity is identified and assessed. It reveals a disconnect between the research metadata that analysts typically use and the research activity they assume they have analysed. The results highlight issues around the responsible use of ‘metrics’ and the importance of analysts clarifying the link between any quantitative proxy indicator and the assumed policy target.

This document has two parts. The **Report** describes key features of the project, presents an overview of the results and summarises the outcomes. The **Annexes** provide more extensive background, specifics on data and methods, and detailed results including figures and tables.

Summary

Research projects that cross disciplinary boundaries (interdisciplinary research, ID research) have been reported (from Subramanyam (1983) onwards) to be increasingly common and are widely considered to be important to the delivery of economic and social impact (studies from ABRC (1987) to King’s College (2015)). However, this report demonstrates objections to the simplistic indexing of interdisciplinarity:

- Diverse concepts and definitions around interdisciplinarity challenge its objective identification and some observers are not precise about the aspect (or component) to which they refer.
- Any one piece of research has many components (e.g. people, objectives, activity, outputs, impacts). Metadata associated with these components have been used to create proxy indicators that are inferred to describe the nature of the research itself.
- Each proxy analysis delivers different insights on the nature of the research project under analysis. The same project may be indexed as interdisciplinary for one parameter (say, departmental affiliations) but not for another (say, diversity of references).
- Analytical indices deliver inconsistent, and sometimes contradictory, results. Some of this variance may depend on the choice of dataset and the application of specific methodology.
- It is essential to consider a framework for analysis, drawing on multiple indicators, rather than expecting any simplistic index on its own to produce an informative outcome.

Many other studies have questioned how ID should be measured (Porter and Chubin, 1985), whether ID proposals tend to suffer in peer review (e.g. Porter and Rossini, 1985; Rinia et al., 2001b), and whether ID research does in practice suffer in evaluation (e.g. van Raan, 2003; Rinia et al., 2011a; Rafols et al., 2012). Running through this is the lack of an objective consensus as to which pieces of work should be deemed 'interdisciplinary'.

One reason for wanting objective, analytical identification of the degree to which a research project may or may not be interdisciplinary is that this would be valuable to research funding bodies, which need transparent and consistent management methodologies to satisfy stakeholder expectations. There would thus be policy and practical significance in demonstrating satisfactory and consistent agreement between different indicators of the distribution, frequency and trajectory of ID research. (For more detail on **Background** see ANNEX A)

The "nature" of large volumes of research activity (as good or poor, useful or trivial) is rarely indexed directly, because that needs expert judgment, so there has historically been widespread use of proxies based on metadata linked to research project inputs and outputs. Without expert, peer agreement, applying indices of the degree of interdisciplinarity may seem abstract, but proxy measures of research activity have been used informatively. For example, it is agreed that relative citation counts reflect research impact. This has created an untested assumption that such proxies can be applied legitimately to other research attributes (see, for example: Elsevier, 2015). The present report challenges the assumption that this can really be informative in an ID research policy context without validation, comparison and careful interpretation.

This report creates such comparisons by drawing on multiple data sources and methodologies. The outcomes reveal not only inconsistencies but also evidence of conflicts between indicators. We conclude that, for the future, it will be essential to be conscious that proxy indicators do not provide direct information about the interdisciplinary nature of the research itself. This compromises their value for management purposes. They provide measures specific to the interdisciplinarity of the metadata, which may or may not be a measure of the activity of interest, and any management group using such analyses should be made fully aware of this distinction. However, although a single definitive indicator will not usually exist, a more sophisticated 'framework' approach to indexing the multiple sources of interdisciplinarity in a project could be very informative.

Methodology

The analytical approach in this study compares a series of indices of metadata associated with inputs (project grants) and outputs (journal articles) and derived from the multidisciplinary nature of research teams (via address lists) and the interdisciplinary nature of research descriptions (via summary text and reference lists). Parts of the analysis were performed independently by Digital Science (London) and by Science-Metrix (Montreal).

A satisfactory index of interdisciplinarity needs information on the variety of disciplines, their balance (or relative frequency) and their disparity (the 'distance' between them), all of which may vary for each dataset to be indexed. For consistency in comparisons:

- Analyses focussed on the UK and a subset of similar research economies: (1) Anglophone group: Australia and Canada; and (2) European group: Germany, the Netherlands and Sweden.
- A common time period (2004-2013) was used insofar as possible.
- Data were aggregated at disciplinary level to a common categorical structure (ANZSRC Divisions - Annex C Table C1).

The project plan was to apply analyses focussed on both multidisciplinary and interdisciplinary indicators to both research grants and research publications (Table 1). This created a two-way comparison between multi- and inter-disciplinary analyses for each data source and between data sources for each aspect of cross-disciplinary interaction. In practice, investigator addresses proved too sparse (italics in Table 1) so a third approach, publication text analysis, was added.

Table 1. Summary structure of the comparative analytical approach. Insufficient data coverage meant that the analysis of departmental addresses of co-investigators on grants could not be completed (see ANNEX B).

	Multidisciplinary (MD) research	**Interdisciplinary (ID) research**
Input funding – grant analyses carried out by Digital Science	*Diversity of departmental addresses of principal co-investigators (PIs)*	Textual analysis of project summaries
Output publications – article analyses carried out by Science-Metrix	Diversity of departmental addresses of co-authors	Categorical analysis of lists of cited references
Output publications – article analyses carried out by Digital Science		Textual analysis of article summaries

Data sources and issues are described in **ANNEX B – Data**. The data sources do not have identical coverage, and both the data content and structure may influence outcomes.

- Grant addresses and summaries were sourced from ÜberResearch's Dimensions database: http://www.uberresearch.com/dimensions-for-funders
- Publication addresses and reference lists were sourced from Thomson Reuters *Web of Science*™

  http://thomsonreuters.com/en/products-services/scholarly-scientific-research/scholarly-search-and-discovery/web-of-science.html
- Publication text summaries were sourced from PubMed: http://ncbi.nlm.nih.gov/pubmed

Methodology used to clean and process these data is described in **ANNEX C - Methods**.

Results – overall field level

The outcomes described by the proxy indicators listed in **Table 1** are inconsistent. Readers unfamiliar with these data and methodologies may wish to refer to ANNEX B and C at this point.

Table 2 summarises multidisciplinary (MD) and interdisciplinary (ID) indices for four analyses at the level of the ANZSRC Divisions and for the aggregate data (the broadest possible overview using the maximum dataset). More results are described in **ANNEXES D**, **E, F** and **G**. An independent analysis (**ANNEX H**) reveals further disparity where a different categorical structure is used.

The sequence in Table 2 is ranked by the results for article reference analysis, applied in this project by Science-Metrix to Thomson Reuters data, as this is probably the most widespread analytical approach in current usage. The table shows a colour spectrum across banded quartiles of the index values, specific values of which are not shown since they imply what appears, in the light of a general lack of consistency, to be spurious precision.

Table 2. Inconsistency in the relative index values given by analyses of interdisciplinarity of research clustered at the level of ANZSRC Division-level Fields of Research (FoR). Index values are colour-banded into quartiles within each indicator set (column): BLUE denotes lower index values in that set; RED denotes higher values.

Source of analysis	Science–Metrix		Digital Science	
Field of Research	Article address	Article reference	Grant text	Article text
Medical & Health Sciences				
Psychology & Cognitive Sciences				
Biological Sciences				
Physical Sciences				
Education				
Commerce, Mgt, Tourism & Services				
Chemical Sciences				
Mathematical Sciences				
Environmental Sciences				
Agricultural & Veterinary Sciences				
Economics				
Engineering				
Earth Sciences				
Studies In Human Society				
Technology				
Language, Comm'n & Culture				
Studies In Creative Arts & Writing				
Law & Legal Studies				
Information & Computing Sciences				
Philosophy & Religious Studies				
History & Archaeology				
Built Environment & Design				

Note that data source and disciplinary variety interact and this is more problematic with selective data-sources: Thomson Reuters *Web of Science*™ data are richer and more fine-grained in science than social science and humanities; PubMed data are richer in bio-medical fields.

The summary results are:

- Negative association between index values for the article address analysis and the three other analyses.
- Inequity in analytical coverage and information due to sparse data for article-based indicators outside STEM subjects.
- Disparities in the correlations between the other analyses. For example:
    - Both Technology and Language & culture have extremely varied outcomes.
    - Environmental Sciences is interdisciplinary on article addresses and project grant text, but mono-disciplinary on article references and abstract text.

Contradiction between indicators does not mean they are invalid. The central issue when reviewing these results is the emerging logical uncertainty about the connection between the metadata for the disciplinary diversity of the associated <u>components</u> and the disciplinary diversity of the underpinning research <u>activity</u>.

- Address diversity for project/publication teams may reflect knowledge brought to bear but refers only indirectly to objectives (e.g. solo researchers can be interdisciplinary; institutional structures vary).
- Text abstracts describing a project grant are close to describing the research activity but provide a limited data-volume for analysis, and full text is not always publicly available. (It is available to the funding body, however, and thus may be a route to better indexing.)
- Outputs (such as articles) contain content, notably reference lists, tuned by authors for specific journals (the same could be true for some monograph series).
- Article abstracts may be more specifically descriptive of research content than a reference list that has been editorially tuned, but the concordance between article abstracts and article content has never been examined.

Results – overall country level

The broad overview (Table 2) contains variance between countries. Table 3 summarises the UK's ID and MD index values relative to the comparator countries, with Germany as a benchmark in volume and performance on e.g. citation indicators.

Generally, the UK tends to have a lower ID and MD index than other countries, though almost invariably a higher index value than Germany, but in some analyses it is closer to the average of the group. On the whole, UK index values rise over the period, though not for every analysis, but they also do so for most countries and this rise may in fact be due to confounded data factors (potentially associated with increased interdisciplinarity, but as yet unproven).

Table 3. Comparison of the MD and ID index values from different methodologies and datasets, for the UK compared to other countries, noting Germany as a comparator of similar volume and focus.

	Other countries	Trend
Research grants text **ANNEX D**	UK ID index similar to other EU countries and slightly better than Germany (Figure D1) UK ID index lower than Australia and slightly better than Canada (Figure D2)	No trend in EU data Slight rise over period in Anglophone data
Article addresses **ANNEX E**	UK MD index below other countries, except Germany, but all above world average (Figure E1)	Steadily rising values for all countries over period
Article reference lists **ANNEX F**	UK ID index was above other countries but recently average in group though always above Germany (Figure F2)	Steadily rising values for all countries over period
PubMed article abstracts **ANNEX G**	N/A	
Nature citing and cited analysis **ANNEX H**	UK ID index higher than Germany but lower than other countries	N/A

Results – UK field level

Inconsistency between fields in relative indicator values also arises when the data are analysed within countries. For example, UK Environmental Sciences index values are low but rising in Anglophone grant data (Figure D3) but high and erratic in the sparser EU grant data (Figure D4). The specific data sample used for analysis evidently influences the detailed outcome, so clearly it is essential to specify the precise analytical context since no result can be assumed to be general.

The data across the different comparative approaches are richest, and therefore most likely to be robust against erratic annual changes and outliers, in the biomedical FoRs. Table 4 reviews the UK's position in Biological Sciences and in Medicine & Health. This shows not only inconsistency in relative standing for these fields compared to other FoRs, but also variation in trend over the period. Furthermore, the deconstruction of medicine/health in the Nature analysis (Annex H) reveals a disparate outcome that may be buried in other analyses.

Table 4. Comparison of the MD and ID index values from different methodologies and datasets, for the fields of Biological Sciences and for Medicine & Health within the UK compared to other countries, noting Germany as a comparator of similar volume and focus

	Field ID results	Trend 2004-2013
Research grants text ANNEX D	Biology and Medicine/Health much lower ID than other fields (Figure D3 and D4)	No trend for EU (Figure D7); rise in Anglophone data (Figure D8) but overall trend (Figure D2) may be due to ICTS and Environmental (Figure D3)
Article addresses ANNEX E	Biology and Medicine/Health higher MD than other fields (Figure E3); very similar ranking for Germany (Figure E4)	Steadily rising values for all fields through period
Article reference lists ANNEX F	Biology and Medicine/Health low within main group around world average (Figure F3)	No trend
PubMed article abstracts ANNEX G	Biology and Medicine/Health well below others at start but less so at end (Figure G1)	Most Divisions steady; Biology rises steadily and Medicine/-Health slightly; strongest Group rise in Biochemistry, but also good in Genetics and Plant sciences (Figure G3)
Nature citing and cited analysis ANNEX H	Health high ID relative to other fields but Clinical Medicine relatively lower	N/A

The influence of data source and structure

Inconsistency in outcomes for different proxy indicators arise overall (Table 2), between comparator countries (Table 3), and for relative values across fields (Table 4). Specific variances can be related to individual datasets (ANNEX D) and to the choice of categorical structures (ANNEX H). Each specific dataset has limitations, but there is generic disjunction between metadata and analytical purpose and a review of the data reveals confounding factors.

- Associations between ID index values, category volume and address count. Global article volume is growing, as are author counts and the number and geographical spread of addresses. These variables affect frequency and disparity and interact with the network structure for analysis. We must infer that the results are compromised until a more complete statistical analysis can demonstrate otherwise.
- Publication data analysis: the MD index increases with higher paper counts at category level (ANNEX E, Figure E2). Countries with higher MD indices also have more addresses per paper (ANNEX C, Table C3). The rise of address count with time could account for the observed rise in MD values.

- Article address analysis: the MD index increases uniformly for all countries (ANNEX E, Figure E1) and for all categories within the UK (Figure E3), Germany and Sweden. Such evenness may be associated with metadata changes, and requires further investigation to account for the variance such changes may cause.
- Article reference list analysis: the ID index increases over time for all countries (ANNEX F, Figure F1). There are no temporal change in relative index values, e.g. for the UK and Germany, confirming that the overall ID change is a global phenomenon. The volume of data on which the index draws grows over time, so a further investigation is essential to explore the variance such changes may cause. The observed increase in index values may be purely volume driven.
- Article reference list analysis also uses a relatively narrow slice of data, which might capture relative outlier records (albeit at a similar rate for each country), although tests show that varying the threshold for this slice has no exceptional influence. However, any narrow slice may tend covertly to capture or to exclude particular parts of the activity portfolio.
- Data choices made about source (e.g. Anglophone or EU grant data) and structure (e.g. FoR or NSF biomedical categories) affect outcomes. Methodological constraints may interact with data use and influence outcomes: reference lists are matched to an analytical database; match rates vary by discipline and affect matched data volume; outcomes vary by country due to journal use; and long reference lists are associated with higher ID index values (Campbell et al., 2015).

Consequently, no single indicator can unequivocally identify and monitor interdisciplinary research activity and no present proxy is a demonstrably satisfactory management tool on its own. A more sophisticated framework approach to research interdisciplinarity is needed that produces information that draws on multiple types of well-curated data.

Conclusions and recommendations

Indicators of interdisciplinarity analysed in this study show diverse inconsistency in terms of change over time, difference between disciplines and trajectory for countries. That raises doubts as to their specific relevance and some cover only some disciplines adequately. Collectively they may be more informative, however, used as a framework to support expert review.

Generally, a single indicator based on proxy metadata will always be too remote to identify or scale the degree of ID research activity: no single indicator has yet been clearly associated with a peer assessment of the interdisciplinarity of the underlying research; such indicators fail a basic 'valid and equitable' requirement since they fail the test of mutual consistency across data sources and methods; and without analytical consistency it is unclear how to achieve peer consensus on what research is interdisciplinary.

Article reference lists are a conventional analytical tool, but possibly the least satisfactory source of indicator data. First, only STEM disciplines are supported by sufficient well-curated data to be properly addressed. Second, our analysis reveals a problematic association between index values and list length (i.e. data volume). Third, match rates, journal usage, and cultural factors may also affect analyses. Fourth, reference lists may not be objective representations of the underlying activity.

It is also unclear whether ID indices based on metadata are equitable for all research modes and all countries. For example:

- Blue-skies research and research near to application and impact do not necessarily exhibit the same structures, outputs and outcomes and cannot be assessed in the same way.
- Smaller EU countries have consistently different index values (in this study) that may be associated with the social culture of research in a smaller domestic community (and this observation could well extend to smaller and larger discipline categories).

Overall, our recommendations are that:

(1) Quantitative proxy indicators of interdisciplinarity based on research activity metadata should only be used in concert, for consistency checking, and should preferably be used in a framework that defines expectations and relationships.

(2) Any analyst of the inter/disciplinarity of research activity should set out clearly their interpretation of interdisciplinarity, the relevance of their particular metadata to that interpretation, and in that context the appropriateness (detail and scope) of their data source and analytical methodology.

(3) Text analysis for research proposals and journal articles, either as abstracts if necessary or preferably as full document text, should be explored as a potential indicator of the research activity.

    a. Text is equally and equitably applicable to all subjects, which author counts and reference lists are not. An obvious source would be article texts, but these are most accessible for STEM subjects. Other publications (books, monographs and grey literature) are appropriate in other disciplines.
    b. Comparison should be made between abstracts and full text, to see whether abstracts adequately reflect the content of the grant proposals and journal articles they represent.

(4) Research funders should include, in their published award information, the departmental affiliations of all principal investigator affiliations, to enable disciplinary diversity of research teams to be evaluated externally as well as internally.

Wagner et al (2011) suggested that 'combinations of quantitative measures and qualitative assessments being applied within evaluation studies appear to reveal [ID] processes but carry burdens of expense, intrusion, and lack of reproducibility year-upon-year … development is needed before metrics can adequately reflect the actual phenomenon of [ID]'. This study wholly supports those conclusions, but we suggest that the more comprehensive internal access that funding bodies such as Research Councils have to their (often confidential) metadata may offer them an amenable route to a set of Wagner's 'combinations of measures' that would satisfy expert committees.

ANNEXES TO THE REPORT

ANNEX A: Background

Research projects that cross disciplinary boundaries (interdisciplinary research, ID research) are considered to make an important contribution to the delivery of economic and social impact (ABRC, 1987; Scottish Universities Research Consortium, 1997; Lyall et al., 2011; Aldrich, 2014; King's College London, 2015). It is also argued that they have long been increasing in frequency (as early as Subramanyam, 1983, followed by arguments about HE Research Assessment Exercises in the 1990s). Studies are equivocal, however, as to how ID should be measured (Porter and Chubin, 1985), whether ID proposals tend to suffer in peer review (e.g. Porter and Rossini, 1985; Rinia et al., 2001b), whether ID research suffers in evaluation (e.g. van Raan, 2003; Rinia et al., 2011a; Rafols et al., 2012), and hence whether ID research can in fact be demonstrated objectively to have lesser or greater impact than other research.

The assessment of the distribution, frequency and trajectory of ID research is therefore of policy and practical significance. For example, for research funders, the relevance of ID research to their objectives is of practical importance. To demonstrate that ID proposals are treated equitably, a reasonable and workable basis for identifying and tracking the progress of those that are more or less MD/ID is required.

The problem of defining interdisciplinarity

Wagner et al (2011) started with a search for quantitative measures of ID research before concluding that ID analysis has been subject to many 'differing definitions, assessment tools, evaluation processes, and measures.'

The primary focus of the present study is on methodology and the consistency of results, not on the specific results themselves (although these throw some light on relative ID levels between countries and fields). The question is whether similar outcomes are produced when the focus of analysis moves between data sources and metadata components. Throughout, the analysis and interpretation returns to a series of basic developmental challenges because this study, like Wagner's, ultimately fails to find a consistent and robust methodology of general applicability.

- There is no universal definition, delineation or simple indexing of ID research.
- An 'ideal' and consistent structure of disciplinary categories does not exist.
  - There is no unique way of categorising 'disciplines' within which 'inter'-actions occur, but such a structure is required to describe 'ID' research.
  - The <u>variety</u> of disciplinary categories, <u>balance</u> between varieties, and <u>disparity</u> (degree of difference) between varieties are core concepts for diversity assessment (Stirling, 2007) and they form the backbone of any index of interdisciplinarity (Rafols and Meyer, 2010).
  - <u>Variety</u> of categories may be few or many depending on granularity. For example, research linking chemistry with physics may seem unequivocally ID but they are both

'physical sciences'; or, within biology, the interaction between ecology and genetics would be hidden at a coarse level, but indexed as ID at a finer level.
    - Evenness/weight of category divisions is subjective. For example, can humanities and science categories be equitably distributed? If chemistry and physics are distinct categories, does engineering form one or many categories? How does it compare to economics?[1]
- The distance (disparity) between categories is problematic.
    - 'Disparity' between discipline categories (conceptual difference or cognitive distance) must be measured to compare specific samples to a global set. To a lay-person, pharmacology and physiology appear similar compared to ceramics, but satisfactory analysis requires consistent quantification.
- The connection between MD teams, ID processes, outputs and outcomes is uncertain.
    - Multidisciplinary (MD) research is distinguished from ID research by some observers. Because of a lack of methodological (and conceptual) consistency it is not clear whether ID and MD research lead to similar outcomes. Besselaar and Heimeriks (2001) argue that both are transitional, dynamic stages in the evolution of new disciplines.
    - In this report: MD implies collaborative working between distinct disciplines (see Qiu, 1992); and ID research implies integrated cross-disciplinary activity.[2] This could also be described as a difference between group structure and functional outcome, or as epistemological and social interdisciplinarity.
- The correlation between proxy indicators and the target activity is contested and optimal indicators have not been agreed.
    - Confidence in the generic utility of citation data is misplaced. Such data are widely used in research quality assessment and, at least in STEM, generally accepted for that purpose.[3] They are also used to index ID research in journal articles via either content (reference lists, looking at research cited) or usage (citations, looking at research users). These are clearly proxies and the degree to which they are satisfactory is long argued (Chubin et al., 1983; Porter and Chubin, 1985).

[1] Marie McVeigh (formerly Director - Journal Indexing, Thomson Reuters) commented on the problem of comparative 'intellectual scale' of the 'Web of Science' global categorical system where 'Economics' and 'Marine Engineering' hold the same hierarchical status for assigning journals.
[2] Other observers (e.g. Wagner et al, 2011) would describe MD and differentiate it from ID research in other ways. In the absence of a consistent convention we stand, for the purposes of this report, on the description made here.
[3] Referencing behaviour and citation rates are strongly discipline-dependent. Citation analysis may correlate with e.g. peer review in (some) STEM areas, but not all. Because of limited coverage in commercial databases, it has very weak analytical power in the humanities.

The problem of indexing interdisciplinarity

A critical problem for any indicator of research activity is to identify the data that are relevant to the activity to be tracked and accessible to the analyst. As for any other research analysis, we look for a data source in the sequence of: (Inputs) → (Activity/Process) → (Outputs) → (Outcomes/Impact).

For the analysis of ID research, Activity/Process is the key stage that is or is not interdisciplinary (ID). If research can unequivocally be identified as ID, e.g. by multiple independent expert review, then the surrounding environment (relevant input and output data) could be sieved for statistical relationships (proxy indicators) that could be used for monitoring.

The problem is that Activity exists in a research 'black box' where there is little sight of the stages between input and output, and expert review has not been applied to a sufficiently large sample. There is consequently no proven test dataset to which proxy indicators could be referred.

Conventional research performance assessment also uses proxies (such as relative financial input and publication output) because of the 'black box' problem. Grant awards and paper acceptances both depend on expert peer review, so high achievement on these variables can be seen as legitimate proxies for 'performance'. However, when proxies are used to 'index' ID research, it is only an implicit assertion, without explicit validation, that data from another research stage (e.g. for an output: the disciplinary diversity of references) accurately reflect the degree to which the activity is also disciplinarily diverse. As noted, this is unproven and contested ground from Chubin onwards. Furthermore, the results of any one analysis, however comprehensive, are compromised because analytical results depend on methodological choices. These depend in turn on the data used, the categories used to bin the data, data filtering or other treatment, or the statistical approach. All can affect results and influence interpretation.

This report therefore uses diverse analyses of different research metadata to create a pool of outcomes from distinct but related perspectives as a basis for comparison (Report: Table 1).

The analysis is structured to compare MD-structure/ID-function. The greater the consistency between these analyses, the greater the confidence that they refer to something fundamental. The greater the variance, the more likely that these are measuring something about the proxy data rather than genuinely indexing the underlying activity (Report: Table 2).

Ideally, for each item analysed (such as a grant or journal article), we would try and compare the scores by each method but this will remain an object for possible future study.

ANNEX B: Data

General data issues, specific source issues and data characteristics

In choosing an appropriate dataset around which an MD/ID Project assessment methodology may be developed, we need data that:

- Are accessible, preferably electronically.
- Extend across a significant time period (for analysis of longitudinal trends).
- Span a broad range of disciplines (which is key to building a complete map of research subject areas from which disciplinary disparity can be estimated).
- Have complete address metadata (for assignment of all investigators to discipline).
- Are indexed with text intact (those without even abstracts are not useful, but abstracts may not be sufficient).

Selection of countries, time periods, and specific data sets is based around these requirements. Data sources and coverage are diverse, to support multiple analytical applications. A series of general issues arise in seeking to acquire data that meet these needs. Although the data sources described here are the most useful for this analysis, a number of challenges are faced in their exploitation including data categorisation, standardising its variety, quantifying its disparity and then measuring the balance across categories.

Both Science-Metrix and Digital Science sought to account for variety, disparity and balance but solutions are not the same and may not feasibly be complete for all data sources. Furthermore, it became evident that <u>disciplinary and structural differences in data coverage</u> could affect the results. For example: Thomson Reuters *Web of Science*™ publications may cover science fields more comprehensively and with greater granularity than humanities; PubMed publications are evidently focussed around medical and biological sciences. In any partial database, more marginal subjects are inherently more likely to be interdisciplinary. Publication abstracts in PubMed records with text that can be tagged as 'Law' universally appear as interdisciplinary because monodisciplinary 'Law' publications are extremely unlikely to be indexed in PubMed. This influence applies to some extent to any non-global data source.

Researcher (and disciplinary) <u>custom and practice</u> affects how information is presented and the degree to which a proposal, description or publication reflects the structure of the underlying project or activity. For example, because journals perceived as relatively high status often exist in disciplinary cores, this can push authors to package papers to that focus rather than capturing the full ID/MD nature in any one piece. Furthermore, an abstract is 'marketing' directed at a potential reader: text analysis of abstracts may produce an ID/MD index that differs from the complete project description or publication text. Finally, national cultural practice in scientific writing may influence style and hence the degree to which text reflects ID activity.

Categorisation is a pervasive issue affecting many research activity and performance analyses. Here we refer to discipline-based categories, but category problems also arise with job roles, institutional types and funding modes. Data are collected and indexed for a variety of reasons under diverse circumstances by disparate agencies. This can make it difficult to bring different parts of an analysis together, using a common structure. At national level this is addressed in part by the OECD Frascati definitions.[4] In practice, for this study, this problem is not insuperable since relative ID levels are analysed at a fairly aggregate level. However, it is an issue to bear in mind for any generally useful methodology.

Distance (disparity) between categories can be properly calculated only by reference to a 'global' dataset that reveals the average co-occurrence of any pair of categories (to which co-occurrences in the sample data are then compared). If the source data are not structured in a way that allows a global reference to be calculated then a proxy measure of disparity is required, which obviously makes the possibly unwarranted assumption that disparity of disciplines is common across systems and data types.

Address analysis is affected by categorisation and by data accessibility. Subject categorisation of addresses is problematic because the addresses relate to local institutional structures including specific centres and generic schools that follow no standard form. Furthermore, feedback suggests that address may be a weak badge of discipline: biology schools recruit chemists and mathematicians, institutional structures change and individuals move (Rafols, 2009).

Addresses on grants may be made more problematic because metadata on co-investigators has not been information generally or uniformly indexed by funding bodies. Analyses of collaborative funding exist, but usually at institutional level and not for subject-based units within institutions.

No 'grant typology' exists or has been widely debated, whereas publications have an established typology of articles, reviews, conference proceedings, books, grey literature and so on. Grants vary in size and scope, in the degree to which they include different aspects of research cost (core staff, project staff, support staff, consumables, equipment, infrastructure costs, etc.) and whether they are directed (part of a defined programme) or responsive (curiosity driven). All these factors could interact with whether the project is structured as ID/MD.

Grant data are variably accessible. Not all jurisdictions yet have policies that make data on publicly supported activity, such as research funding, openly available. In some cases the readiness to expose such data may be partial, covering only some agencies or some programmes, or on a basis unhelpful to analytics.

[4] The 2015 OECD Frascati Manual is available at http://www.oecd.org/publications/frascati-manual-2015-9789264239012-en.htm

Grant metadata are variable. The issue of co-PIs (noted above) is one problem since in the absence of disciplinary affiliations for all investigators the MD analysis is constrained. Furthermore, the extent to which descriptive text is accessible is driven not only by grant size (with less information for small grants) but also by variable local policies. The volume of descriptive text influences the ID/MD analysis.

Length of reference lists is a significant problem in which data and analysis are multiply confounded. A longer reference list provides more data points for analysis; not all references are actually indexed in the source database (because they are not all journal articles and because not all journals are covered); thus, a longer reference list also provides more usable data. Longer lists enhance analysis and short lists may provide little useful data. However, there is an apparent positive correlation between the degree of interdisciplinarity and the length of reference lists (Campbell et al, 2015). To overcome the influence of this interaction, it is possible to apply a cut-off, restrict data to papers with a reference list of some minimum size, and then apply this uniformly. Even so, a caveat is that there may be journal factors (editors can restrict reference lists) and cultural factors (both the disciplinary tendency to reference and the predominant length of research reports) that would affect the balance of data samples.

Access to full text for journal articles would provide a third route to ID analysis, independent of author addresses and reference lists, and providing comparability with full text analysis of project grant descriptions. However, at this time, such full text analysis is not generally available for a wide sample of journals by region and subject.

Countries covered in this report

Countries were selected to increase the comparability of methodological outcomes and to compare UK research with two groups of similar, globally competitive research economies. A broader global comparison would tend to add sources of difference. Data were sought on:

- Australia and Canada are Anglophone countries with university-focussed research bases similar to the UK. This group has significant comparability via historical links, inter-mobility of staff, similar research base structures and extensive shared literature. Because of the common structures, grant awarding also bears reasonable similarities. The major problem is relatively recent changes in research and funding policy, especially in Canada; this points to a possible more general challenge to finance data utility and comparability.
- Germany, the Netherlands and Sweden are European countries sharing the UK regional policy environment. This group operate in the same region, have extended historical development and political structure, but are more varied in institutional structure. While the UK, Netherlands and Sweden have a strong university research base, Germany has a strong suite of mission-led research institutions (such as the Max Planck and Helmholtz networks) that creates structural differences in diversity.

- UK data for comparison with both these.

Factors appear to come into play for small countries and perhaps for smaller discipline categories (but note that categories may or may not map well onto real community networks) that then affect indicator analyses. When a researcher looks for collaborators in a small network/economy they may spread their net more widely than in a country/field where there are larger networks. That may also influence the national policy environment and hence funding and other behavioural drivers.

The input (funding) data in this report

Input data were sourced from the ÜberResearch *Dimensions* database of research grants and analysed by Digital Science. These records contain information on principal investigators (PIs), their affiliations, the project title and description, the start and end dates, the size of the grant and the awarding body.

- Data available varied considerably between countries due to differences in national research policy, the ways in which funding is distributed and – consequently – the ways in which data are presently accessible.
- Affiliation data is often only publicly available only for the lead PI, not the other principals, usually because this affiliation identifies the contracting organisation to the funder (holding the original database). Consequently, the analysis of MD teams via the categorisation of investigator addresses cannot be generally applied. (A more comprehensive analysis could be done within funding body databases but it would lack global reference for disciplinary disparity.)
- The funding data available for Australia and Canada were relatively comprehensive. However, the funding of university research in Canada has changed relatively recently; that academics have to source more of their own salary to support research activity; there are also many small project grants. *Ad personam* and small grants are innately less likely to engage MD teams because of their focus. Many smaller grants lacked sufficient text and metadata for analysis, however, and were therefore omitted from consideration.
- For the European comparators, research grant data available through the various national/regional funding agencies are not yet comprehensive, which reduces comparability significantly. It was therefore necessary to reduce the scope of the UK-Europe comparisons to focus only on grants sourced on a common basis through the European Commission Framework and European Research Council programmes.

The output (publication) data in this report

Output data were journal articles:

- Sourced from Thomson Reuters *Web of Science*™ (WoS) and analysed by Science-Metrix.
- Sourced from PubMed and analysed by Digital Science.

Note that journals are not the primary medium of research communication for the arts, humanities and most social sciences. Databases such as WoS and Elsevier's Scopus have only a fraction of the journal article publications published in the arts and humanities and only some of the social sciences (i.e. primarily excluding economics).

WoS data were reduced to citable documents (i.e. excluding proceedings and journal ephemera). Records contain information on: authors, their affiliations, journal information; and reference lists.

- Author affiliations are reliable but the discipline of the author and the discipline of the affiliation are not universally synonymous: Rafols (2009) provides examples of this.
- WoS journal categories are clusters of serials with a high level of co-citation. This supports 'search and discovery' and usually mirrors disciplines recognised by researchers but the granularity is finer in STEM than elsewhere and does not generally mirror institutional structures in affiliation/address data, which therefore require separate categorisation.
- WoS cannot cover all the sources in reference lists of articles that it indexes. A variable fraction of any article's references are indexed (this is worse for data sources that have less historical depth) and this fraction is not uniformly distributed across years and research categories.

Article data were sourced from PubMed so that abstract text could be analysed by Digital Science

- PubMed records are focussed on clinical, biomedical and health research and therefore provide both a disciplinarily limited data source and therefore a limited and unbalanced global network in relation to general research disciplinary diversity.

ANNEX C: Methodology

As noted in Annex A, for the assessment of interdisciplinarity, Stirling (2008) has drawn attention to the need to describe disciplinary variety, to account for the balance (or relative frequency) of these varieties and to have a reference background to measure disparity (or the distance between the varieties). A significant part of methodological development is about accounting for these measures.

Variety – categorising disciplines

To standardise the diversity assessments in this report, insofar as possible, a common structure was agreed for the 'variety' of disciplines. This used the discipline category structure set by the Fields of Research (FoR) within the Australia and New Zealand Standard Research Classification (ANZSRC, 2008). The ANZSRC system is independent of any commercial data structure and has been widely adopted by analysts. It is a hierarchical classification of subject-based categories for which the Australian Research Council secretariat worked with academic experts to map journals by field and subfield of research.

Table C1. ANZSRC Division-level Fields of Research used as subject categories to collate data in this study. The short names used in figure legends elsewhere in the report are also shown.

ANZSRC code	Division name	Figure legend short name
01	Mathematical Sciences	Maths
02	Physical Sciences	Phys Sci
03	Chemical Sciences	Chem Sci
04	Earth Sciences	Earth Sci
05	Environmental Sciences	Env't Sci
06	Biological Sciences	Biol Sci
07	Agricultural and Veterinary Sciences	Ag & Vet Sci
08	Information and Computing Sciences	Inf & CS
09	Engineering	Engineering
10	Technology	Technol
11	Medical and Health Sciences	Med & HS
12	Built Environment and Design	Blt Environ
13	Education	Education
14	Economics	Economics
15	Commerce, Management, Tourism and Services	Commerce
16	Studies In Human Society	Human Soc
17	Psychology and Cognitive Sciences	Psychology
18	Law and Legal Studies	Law & Legal
19	Studies In Creative Arts and Writing	Creative Arts
20	Language, Communication and Culture	Language
21	History and Archaeology	History
22	Philosophy and Religious Studies	Phil & Theol

The ANZSRC system has a hierarchy of categories: Divisions (2 digit level) are 22 broad areas, e.g. "01 Mathematical Sciences", while Groups (4 digit level) are 157 detailed sub-areas, e.g. "Pure Mathematics" lies within "Mathematical Sciences"; and there is a further more specific layer of 1,238 Fields (6 digit level).

Issues of balance and disparity are complex and are dealt with differently according to data source and metadata associated with the records for grants and articles.

Assigning variety to funding and PubMed article data

A number of variables need to be identified for all the analytical data, including dates and locations. Of these, a standardised assignment of variety is the most challenging because data compilers use different categorical structures.

In analyzing text (for a grant or an article summary), Digital Science can algorithmically assign fields but does not apply a balance count to these assignments. In other words, phrases in a summary text may associate it with 'physical sciences' while other phrases associate it with 'biological sciences'. However, numbers cannot then be assigned to describe the balance between the two: there is no robust notion of balance in varietal assignments from a single text section.

ÜberResearch's Dimensions platform indexes funding data from a variety of sources. Each research grant (or award) is associated with a country through the institutions that receive the grant. Each has a start date (used in this analysis) and has or will later have an end date. The co-investigator address metadata proved to be too sparse to provide enough information for any comparative MD team analysis: most funding bodies provide detailed investigator address data (disciplinary structure within the host organisation) only for the contractual lead PI and not for co-investigators. The analysis would be entirely feasible if all co-investigator address were published, but a large number of funding bodies would need to do this to make the dataset sufficiently global.

For the research grant text analysis, the data were extracted from the Dimensions system in July 2015. The annual count for comparable Anglophone countries with good temporal and subject area coverage suggests that data for 2006-2013 were sufficiently well populated for informative analyses. The aggregated USD value of these reflects the much larger relative size of the UK research base. There was also a declining trajectory for Canadian research grants, due to changes in research policy and funding. The figures suggest that Canada has an increasing frequency of relatively low-value funding awards, which we believe is associated with *ad personam* research support rather than specific activity and grant awards. However, funding modes are not readily separated.

Abstracts from the PubMed publication database were extracted at the end of 2015. This database has good coverage back into the 1990s and is focused in the biomedical sciences. It presently contains records for around 10 million articles.

The text for the grant and article abstracts was classified and tagged with between zero and five ANZSRC FoR Group 4-digit level categories. All analysis in this report relies on the classification at this level but for overviews, or where data are sparse, some results are aggregated to the higher level Divisions. The classifier relies on supervised machine learning: the algorithm has 'learnt' to recognize text associated with FoR Groups through exposure to manually classified text. The technology was applied and manually validated for the analysis of REF impact case study text (King's College London, 2015) and subsequently updated.

After assigning FoRs to each abstract in a dataset, the spread was aggregated across FoR Divisions as a percentage count (and percentage value for grants). For PubMed articles, national differences were not evaluated as the purpose was to test the feasibility and generic outcome of text analysis of interdisciplinarity when applied to a specific article set.

For grants, differences between countries in the relative spread of resource across subject areas are expected, because of historical and policy differences and the degree of specialism in national portfolios. However, the broad impression is of a similar balance of activity for the three Anglophone research economies. Australia appears to give a particular emphasis to medical and health sciences but this is also the Division with the greatest level of activity for Canada and the UK so this is a matter of degree rather than substantive difference.

The global grants' set cannot be pooled because European research funding data were not as broadly based as those for the Anglophone countries and the balance of block grants and project grants also differs. There is a usable volume of grants in core natural sciences, engineering and ICT (which collectively account for two-thirds of the data by count of awards) but other Divisions are sparser. Comparable analyses for the UK and other countries can be performed, however, because the coverage is derived from the same set of funding programmes for each country.

Calculating disparity for funding and PubMed article data

A reference structure is required to introduce a measure of disparity (the conceptual distance between disciplinary varieties) to the calculation of an ID index because there is no common structure. The same methodology was used for calculating disparity in the Dimensions grants data and the PubMed article data.

The Anglophone and European funding data are only partial sets, albeit for historically well-established research economies, so it might reasonably be argued that even collectively they would not reflect a 'global' pattern of funding disparity since the priorities of e.g. BRIC economies might differ markedly and the emergent pattern of global interdisciplinarity would then diverge. However, this is the most informative data source available and by aggregating the total Anglophone and European data we arrive at the best available 'global' reference.

The PubMed article data are evidently a partial set since the data base is specifically established to support medical and related sciences. However, it is global in coverage.

Given a set of objects with known FoR classifications, we can use the objects themselves to look for similar FoR Groups: if two FoRs often appear on the same objects, then we define these as being more similar to each other than two FoRs that rarely appear together. The search is extended to overlapping classifications across the full set of 157 Group-level FoRs. Mathematically, we use vectors to represent FoRs in terms of their overlap with other FoRs. To go from these vectors to a numerical measure of distance we choose to use the cosine distance. This gives a numerical distance ranging from 0 to 1 between all 24,492 FoR pairings. Two FoRs with a distance of 1 are maximally separated (they never appear together), and two FoRs with a distance of 0 are as close as possible (they always appear together). The sense of this is shown by examples of the closest pairs, with the smallest distance measure, and the most distant pairs, that never appear together. The 'distances' in these data fit with intuitive expectations of cognitive distance.

Table C2. Most similar FoR pairs in terms of the likelihood of being found together in an abstract on the same Dimensions grant.

Curriculum & Pedagogy	Specialist Studies In Education
Language Studies	Linguistics
Geochemistry	Geology
Plant Biology	Crop & Pasture Production
Applied Economics	Econometrics
Historical Studies	Literary Studies
Visual Arts and Crafts	Art Theory & Criticism

Table C3. Most distant FoR pairs that never appear together in an abstract on the same Dimensions grant.

Transportation & Freight Services	Agricultural Biotechnology
Cultural Studies	Other Earth Sciences
Agricultural Biotechnology	Astronomical & Space Sciences
Inorganic Chemistry	Art Theory and Criticism
Quantum Physics	Commercial Services
Theoretical & Computational Chemistry	Social Work
Medical Microbiology	Engineering Design

For the purpose of an interdisciplinary index, the separate disparity measures between up to five FoR classifications (that is up to 10 distances) must be aggregated to a single number. This allows us to comment on, say, the interdisciplinarity of the grants' text associated with Biological Sciences, and compare this year on year.

To create a single distance (cf. disparity) measure for an object (a grant or article summary text) we choose the maximal distance of the (up to) 10 possibilities, for the relevant grants or articles dataset[5]. This gives a sense of the closeness of the most uncommon combination of FoRs that are seen together. Taking the maximum distance, representing the most disparate disciplinary combination, as our measure of interdisciplinarity at the object level, we are able to order all objects according to their interdisciplinarity score. We then use the ratio of objects with disparate FoRs to those with only "close" FoRs, to index the interdisciplinarity of a group.

Assigning variety and calculating balance in *Web of Science™* publication data

For the purposes of denoting varieties in this analysis, each journal in Thomson Reuters *Web of Science™*, normally assigned to standard commercial categories, are reassigned to the ANZSRC system.

Both the MD and ID index are based on the integration metric of Porter & Rafols (2009; see also Rafols and Meyer, 2010) to quantify the diversity (i.e. variety, balance and distance) of disciplines in, respectively, the departmental affiliations of a papers' authors and its reference list. It consists of measuring the diversity of disciplines relative to a reference set of papers.

Article addresses

The MD index computed by Science-Metrix uses the author address fields associated with each articles and review in the entire Web of Science. Author addresses are allocated to disciplines based on their departmental affiliations. Careful judgement was required to assign address to discipline. In a first step, addresses were manually attributed to a discipline using department names. Building on this seed, the manual attribution of disciplines was validated using an algorithm which re-classified each departmental address to the core groups of disciplines established in the first round. This algorithm computed an affinity score (Archambault et al., 2011) for each pair of departmental addresses and disciplinary groups to identify the most relevant. Where the most relevant group differed from that assigned via manual attribution, verifications was required and a final decision was made as to classification. Subsequently, this approach was used in a second round to attribute the departmental addresses that were not initially treated in the manual attribution.

Some 129 distinct disciplines (or department types) emerged (these are not based on the FoR classification, but rather reflect the most common departmental structure found in HE institutions).

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[5] Measures of the average (mean or median, specifically) across the set of distances associated with any one object are correlated with the number of distance measures between FoRs for that object. This means that for an object with five FoRs we are more likely to find that the average distance is greater than for an object with just two FoRs. The maximum distance gives a better sense of the interesting FoR combinations.

The number of occurrences of each of the 129 disciplines within the departmental addresses of a publication was then used to create a publication vector.

This vector was used to compute the MD index of each publication using the integration metric of Porter and Rafols (2009). The multidisciplinarity of each publication within the database is thus measured by comparing the frequency distribution of disciplines within its departmental addresses to a proximity matrix between disciplines (pairwise similarity of the 129 disciplines based the distribution across FOR subfields (journal categories) of each of the 129 disciplines based on the publications falling in each disciplines based on their departmental addresses (note the attribution of publications across disciplines based on departmental addresses is not mutually exclusive).

This approach gives more weight to unusual co-occurring disciplines relative to those that are common. In other words, a publication authored by researchers from Microbiology and Religious Studies will have a more multidisciplinary index than one authored from Microbiology and Immunology. Using this computation method, each publication was given a MD value ranging from 0 (monodisciplinary) to 1 (highly multidisciplinary). Subsequently, the MD of an entity (e.g., country) is obtained by averaging the scores of its publications.

The average percentage of a publication's departmental addresses that have been successfully classified was analysed across research field (FoR), year and country to identify potentially problematic biases. Science-Metrix observed no important biases that made it necessary to normalise the papers' MD scores (see below).

Table C4. Average number and average percentage of classified addresses per paper for select countries (2004 – 2013). Source: Computed by Science-Metrix using Thomson Reuters Web of Science™ *data*

Selected countries	Average number of classified addresses	Average number of addresses	Average % classified addresses/paper
Australia	3.08	4.66	74%
Canada	3.25	4.79	77%
Germany	3.09	4.88	74%
Netherlands	3.69	5.80	74%
Sweden	3.79	5.73	77%
United Kingdom	3.06	4.74	75%

Table C5. Average number and average percentage of classified addresses per paper in Thomson Reuters Web of Science™ across Fields of Research (FoR) for select countries (see Table C4) (2004 – 2013)

FoR Group	Average number of classified addresses	Average number of addresses	Average % classified addresses/paper
Physical Sciences	3.29	6.34	69%
Medical & Health Sciences	3.15	4.28	78%
Unclassified	2.69	4.21	74%
Multidisciplinary	2.92	4.19	74%
Biological Sciences	2.85	3.83	78%
Earth Sciences	2.42	3.70	70%
Technology	2.57	3.62	74%
Environmental Sciences	2.43	3.62	72%
History & Archaeology	2.24	3.45	69%
Agricultural & Veterinary Sciences	2.29	3.32	73%
Psychology & Cognitive Sciences	2.44	3.27	78%
Education	2.15	3.12	73%
Mathematical Sciences	2.31	3.08	81%
Chemical Sciences	2.34	3.07	79%
Engineering	2.11	3.00	74%
Studies In Human Society	2.01	2.98	71%
Economics	1.98	2.88	73%
Information & Computing Sciences	2.11	2.87	77%
Commerce, Management, Tourism	2.00	2.78	76%
Studies In Creative Arts & Writing	1.77	2.76	68%
Law And Legal Studies	1.86	2.74	73%
Built Environment & Design	1.85	2.70	73%
Philosophy & Religious Studies	1.88	2.69	73%
Language, Communication & Culture	1.56	2.46	67%

For Thomson Reuters *Web of Science*™ database as a whole and for the countries selected for analysis in this study, an identification/classification rate between 70% and 80% was achieved for each data year. The average number of address increased from 3.1 in 2004 to 3.7 in 2013, with the number of classified addresses increasing from 2.4 to 2.7. The numbers of addresses was slightly higher for the select countries, rising to 4.6 in 2013 but with only 74% being classified compared to 78% overall. There are on average more addresses on publications with Netherlands and Swedish co-authorship than on other papers. There is very little difference for the average address count for the other four countries. The number of addresses per publication was higher on average in natural sciences but the percentage classifiable showed no clear pattern.

Article reference lists

For the analysis of article reference lists, the ID index computed by Science-Metrix uses the FoR disciplines (4-digit). The ID score of each publication within the database is measured by comparing the frequency distribution of subfields within its references to a proximity matrix between disciplines (pairwise similarity of disciplines based on their co-occurrence patterns within the references of individual publication in the database as a whole).

This approach gives more weight to unusual co-citation patterns relative to those that are very common. As such, a publication co-citing publications from the subfields of plant biology and law would have a higher ID score than one co-citing papers from the subfields of plant biology and pharmacology & pharmaceutical sciences.

Applying this computation method, each publication receives an ID score ranging from 0 (mono-disciplinary) to 1 (highly interdisciplinary). Subsequently, the ID of an entity (e.g., country) can be obtained by averaging the scores of its publications (the general behaviour of the entity) or by computing the proportion of its publications falling within the 10% most interdisciplinary in the database (the degree to which the entity produces highly interdisciplinary work).

A correlation has been observed between the number of references indexed in the commercial source and the average ID score of publications with a given number of such references. Reviews behave differently in terms of the number of references they typically include and this could be a reason for rejecting reviews and analysing only articles. This was not found to impact the metrics, however, and in this instance reviews were retained in the analysis.

It is known that Thomson Reuters *Web of Science*™ data include a relatively greater number of science/technology journals than of social science/humanities journals. Consequently, the likelihood of matched and unmatched references must vary across disciplinary boundaries. Science-Metrix has shown that "interdisciplinarity" scores increase rapidly from publications having zero classified and matched references to publications having 30 or more references matched to journals in the database (the ID scores are understood to present a slight and linear increase beyond that point, although the variation by field is unspecified). Important biases could therefore prevail when using the average of the "interdisciplinarity" scores across an entity's publications.

Note that more than one effect is in play. It may be that the ID score rises with match rate (because a greater number of references will reveal links to more categories) and it may be that ID papers are innately more likely to have longer reference lists (because ID research necessarily draws on a greater number of categories, requiring more referencing). Whatever the driving factor, the solution is to enable greater comparability between samples. In prior studies (e.g. Campbell et al., 2015), Science-Metrix has dealt with the issue by:

- Normalising the ID score of papers by their number of classified references (which here led to an over-normalisation of the scores).
- Analysing in each category the 1% of papers with the largest number of references to ensure that:
  - Few papers in any category have fewer than 30 classified references.
  - All categories are represented proportionately to their overall occurrence.
- Computing an aggregated ID metric for the proportion of retained papers falling in the 10% of papers with the highest ID score (typically scores of at least 0.70) subject to threshold volume of 100 papers.

A similar approach was applied to Thomson Reuters *Web of Science*™ data in this study. A downside of omitting papers with only a small number of references is that 'variety' (the number of distinct disciplines identified by article references) might be given less weight than the 'balance' and 'distance'.

A further analytical constraint on computing the ID metric becomes apparent at a disaggregated level. The volume filter (i.e. the 1% of papers with the largest number of classified references in each category) markedly reduces the possibility of providing reliable data by year and by FoR. Relatively small samples of the initial article population are retained for analysis and many index values appear as not applicable because the final sample size is less than 100 articles.

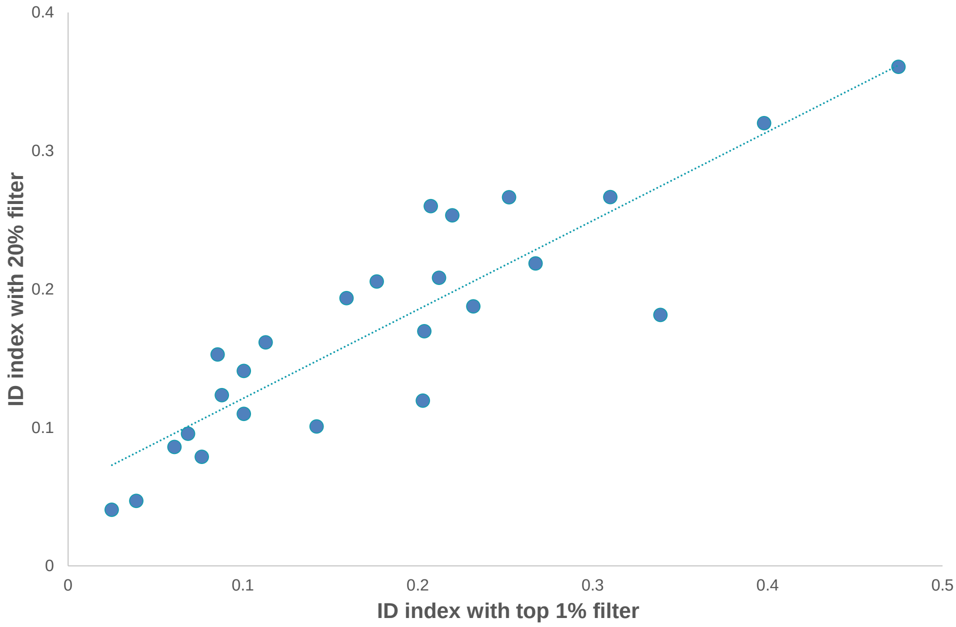
To reduce the number of not applicable cases, less stringent filters were applied:

- Limit at the 10% of papers with the greatest number of classified references in each category
- Limit at the 10% of papers with the highest percentage of classified references in each category (this also retains the emphasis on 'variety')
- Limit at the 20% of papers with the highest percentage of classified references in each category (again retaining emphasis on 'variety').

The 1% threshold may cause some concern as it focusses the analysis on what might be seen as an outlier group of papers. While these would be comparable outliers for each sample, and for categories within each sample, there would nonetheless be reasonable doubt that they were truly representative. Reducing the threshold to 20% makes the data more representative while retaining reasonable albeit less clear-cut comparability.

Science-Metrix tested data in this report aggregated at the ANZSRC Division level and considered the share of 10% most interdisciplinary articles for 2004–2013 by category (i) among the 1% of papers with the largest number of classified references by field of research and (ii) among the 20% of papers with the largest percentage of classified references at world level. Some fields (e.g. Earth Science, Agriculture) appear less ID, whereas (Philosophy & Theology, Economics) appear more ID at the 1% than 20% level. Both by category rank and by percentile within category, however, the overall correlation between results with the 1% and 20% filters is highly significant ($P<0.001$). (Figure C1; see also ANNEX E, Figure E1)

Figure C1. Relationship at FoR Division level between the ID index for articles with reference lists limited at a threshold with the 1% longest reference lists and 20% longest reference lists. This trend is statistically significant (rank correlation: $r^2=0.77$, $P<0.001$).



These approaches were used to study trends in the absolute ID scores of papers by FoR and year for all countries (i.e. world trends) as well as by country and year for all FoR combined. However, when moving to the country level by FoR and year, the filters applied substantially reduce the population size available to compute the ID scores and this could affect the accuracy of the metric. In this case, a normalisation procedure was used to study trends relative to a world reference. This allows all papers to be retained (no filter) but does not inform the absolute ID scores. For instance, if the relative score of a country is rising relative to the world in a given FoR, the absolute ID of the country might actually be declining if the corresponding ID at world level is decreasing even faster.

To present data for all categories of disaggregated data (i.e. by country, year and FoR) as well as to eliminate the biases in the database, Science-Metrix implemented an approach similar to the one it has used to compute the scientific impact of research entities (i.e. the Average of Relative Citations [ARC] indicator). The interdisciplinary scores of papers were normalised by the average interdisciplinary scores of all papers in their corresponding subfield and year. Although this approach effectively removes some bias attributable to coverage issues (discussed above), it does not allow differences to be observed in absolute ID scores, only differences relative to the world reference level (i.e. score of 1). However, it does enable trends to be monitored regarding the extent to which countries deviate (positively: score > 1; or negatively: score < 1) from the world level by field of research or year.

ANNEX D: Input interdisciplinarity – grant summaries

SUMMARY. *The calculated values of an interdisciplinary (ID) index based on text analysis of research grant summaries show no strong overall change during the decade 2005-2014. In both the European group and the Anglophone group, the natural science and technology disciplines have higher ID index values than the social science and humanities. The UK has a higher average ID metric than other large research economies but lower ID than smaller economies. This holds true for a detailed examination of the ID metric in Biological sciences, where again the index fluctuates and may increase somewhat but does not significantly change in either dataset.*

There is no multidisciplinarity (MD) index for the awards data because, as noted elsewhere, the address data for co-investigators were insufficient to support the analysis of departmental locations.

The ID index is based on text analysis that identifies FoRs (variety) at the 4-digit Group level within the ANZSRC system and measures the distance (disparity) between these. The balance between FoRs cannot be measured with these data. Some national agencies publish (or require) more extensive grant summaries than others so there is some diversity in the relative volume of information available from different sources. The UK is compared separately with Anglophone and with European research economies. In the EU data, it has around 500 grants per year to 2010 and about 1,000 per year thereafter. In the Anglophone data, it has about 8,000 grants per year.

There is considerable year-to-year variation for smaller economies (Netherlands, Sweden and Australia) but more consistency for the UK and larger economies (France, Germany and Canada). There is no strong temporal trend in the 'grand' averages for any country but – even setting aside the initial steep increase – the UK has a slight progressive increase in ID in the Anglophone dataset which is not seen in the European data.

The substantial annual variation in the ID index across fields for the UK (and the other three larger economies from both subsets of grants) makes it difficult to discern common patterns but the most general pattern seems to be one of fluctuation rather than clearly rising or falling trends. At field level, Inf & CS and Maths have a high ID value while Medicine and Biology have low values.

Figure D1. European research economies: average interdisciplinarity index from analysis of grant summary text data. The data displayed here are for all grants awarded to that country in each year. Index similarity between, and its variation within, countries suggests there is little differentiation.

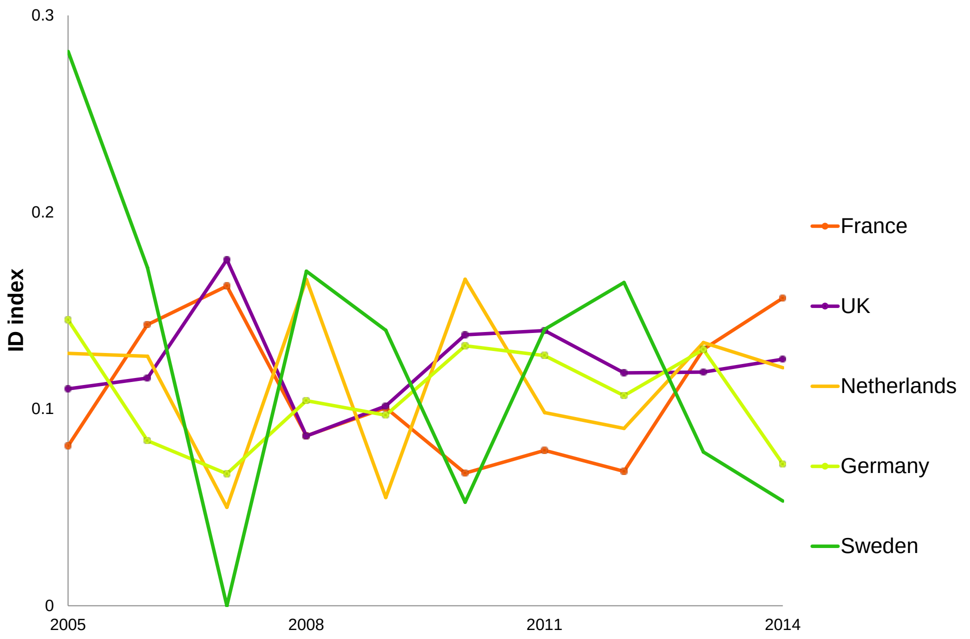
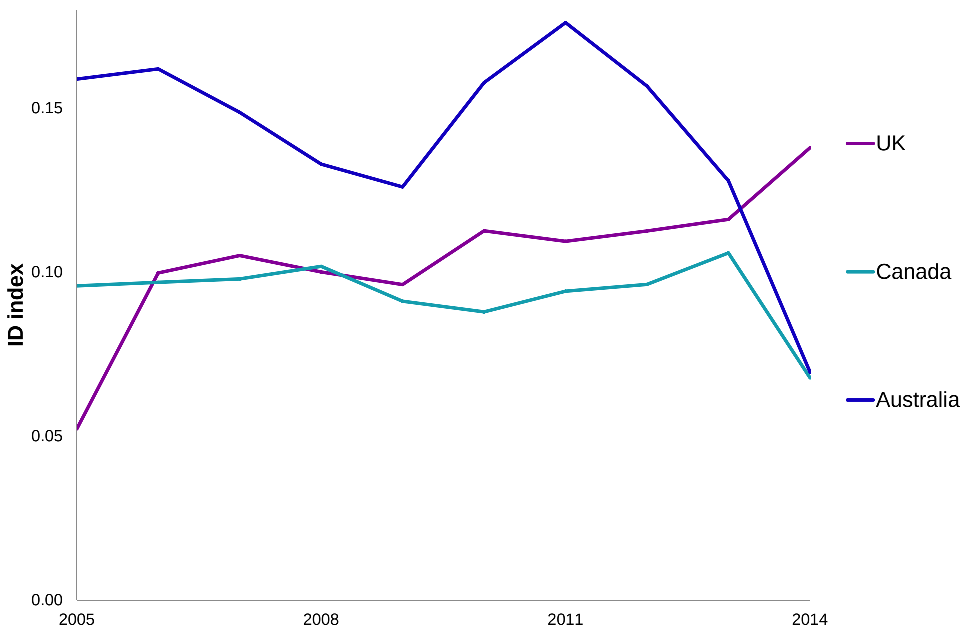


Figure D2. Anglophone research economies: average interdisciplinarity index from analysis of grant text data. The data displayed here are for all grants awarded to that country in each year. While there is little differentiation between UK and Canada, Australia appears to have consistently higher levels of interdisciplinarity.



The count of country data for each FoR Group by year is relatively sparse, so the Group data have been aggregated at Division level for further analysis. This does not affect the calculation of the ID index because disparity between Groups within a Division is calculated in these data. The data are also shown as three-year rolling averages (Figure D3 onwards) because of the year-on-year fluctuations seen in Figure D1. (For similar reasons, citation data have frequently been reported as five-year rolling averages even at Division and country level.) The relatively smaller Divisions (often social science and humanities) tend to have erratic data and have been omitted.

At FoR level, the average ID index of grants linked to Mathematics and Earth sciences is generally higher than for other Divisions while Information Science (ICTS) is usually in the middle and the index for Technology tends to be lower. The position of other fields is variable as, for example, UK data in Figures D3 and D4:

- Agriculture and Veterinary Sciences has a low ID index (around 0.1) in the Anglophone data but a higher value and trajectory rising to over 0.2 in the EU data;
- Environmental Sciences are on a rising trajectory in the Anglophone data but not in the EU data.

The ID index values for the UK are mostly around 0.1-0.2 in both datasets and the FoRs above this are Information Sciences and Mathematics in both. Canada generally has higher ID index values across the spread while France and Germany have lower interdisciplinary indices.

Figure D3. UK grants in the Anglophone data-set: interdisciplinarity index (3-year rolling window averages), by ANZSRC at the Division subject-area level.

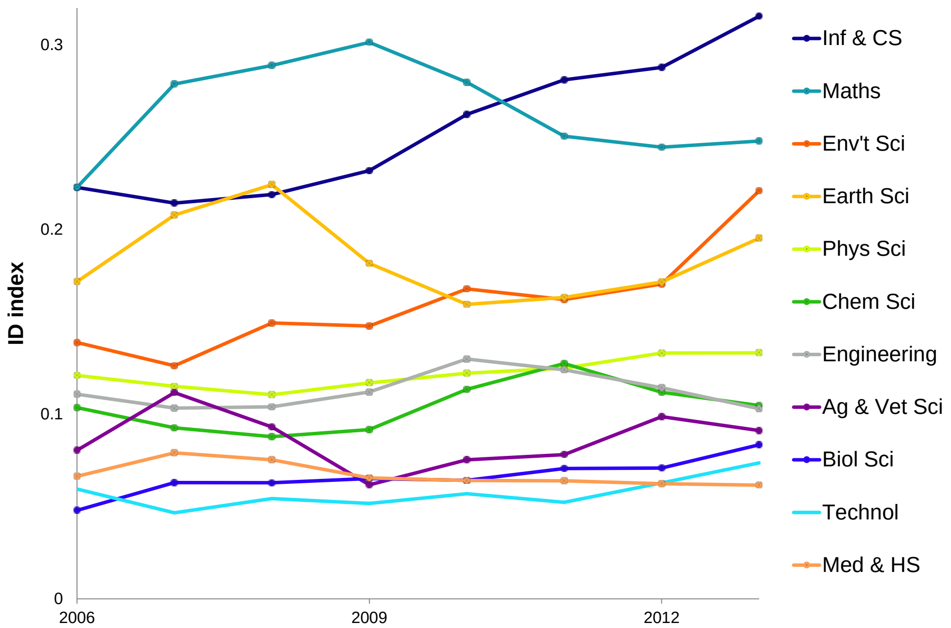


Figure D4. European grants awarded to the UK: interdisciplinarity index (3-year rolling window averages), by ANZSRC subject area Division.

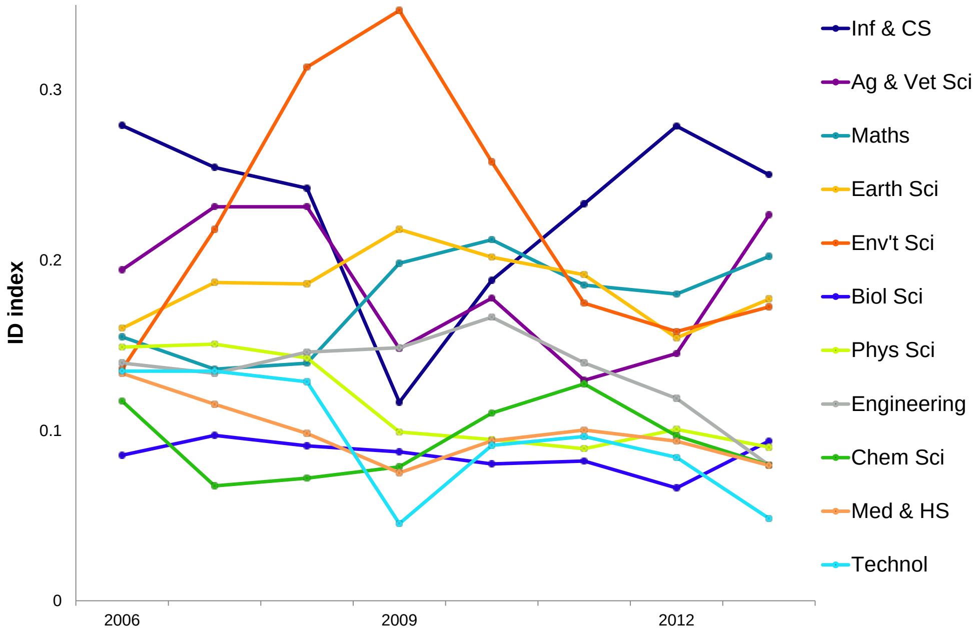


Figure D5. European grants awarded to France: interdisciplinarity index (3-year rolling window averages), by ANZSRC subject area Division.

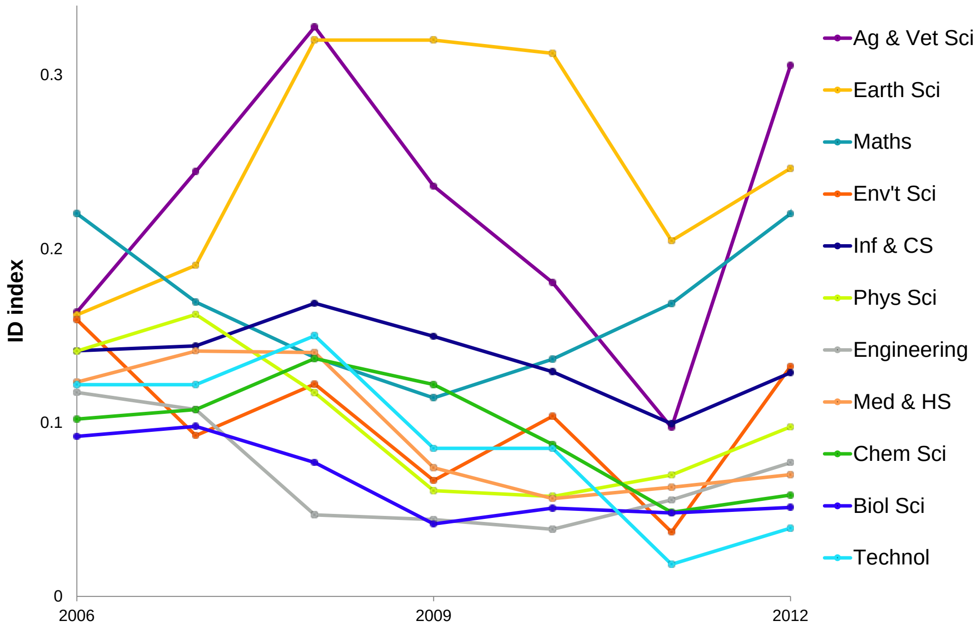
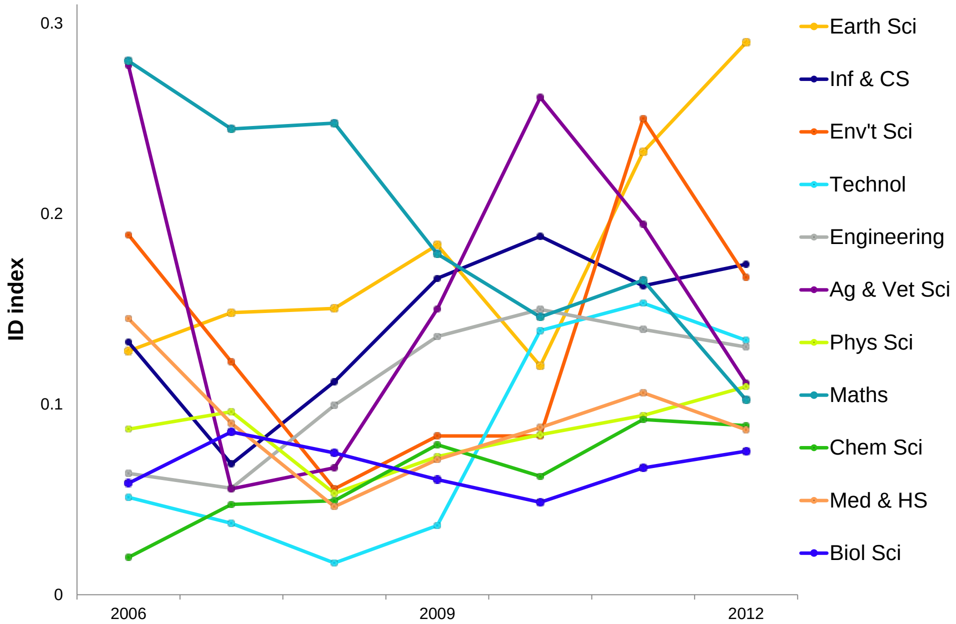


Figure D6. European grants awarded to Germany: interdisciplinarity index (3-year rolling window averages), by ANZSRC subject area Division.



Direct comparisons can be made at field level: for example, Biological Sciences (Figure D7), the Division with the most abundant data. This example includes Spain as well as the UK and the four standard comparators (France, Germany, Netherlands, Sweden) as its data had a similar pattern to the Netherlands, which differed from the other comparators

For the European data, there is no temporal trend in the UK's ID index for grants that are associated with Biological Sciences. It is also evident that the UK generally has a somewhat higher ID index in Biological Sciences than does France or Germany, and that neither of these comparators shows any temporal trend. Sweden appears to have slightly higher ID on average but the index is volatile and there is no consistent trend. However, for the Anglophone data (Figure D8) there is a rising ID trend for the UK and Canada. In Europe, Netherlands and Spain also display a progressively increasing ID index over the period for which data are analysed from somewhat less to somewhat more than the UK. The value of the ID index for the UK is rather less than 0.1 in the European data and rising from 0.5 to a similar value in the Anglophone data.

Figure D7. Biological sciences: index of interdisciplinarity in grant text data for European research economies. The data displayed here are three-year rolling windows for the average ID index for grants assigned to an FoR Group that falls within the ANZSRC Division of Biological Sciences.

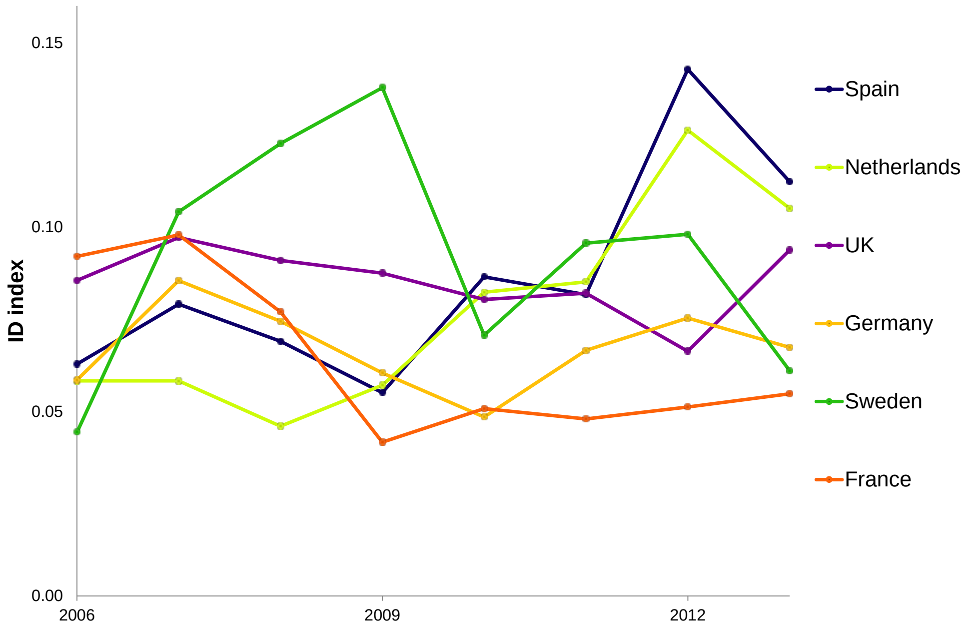
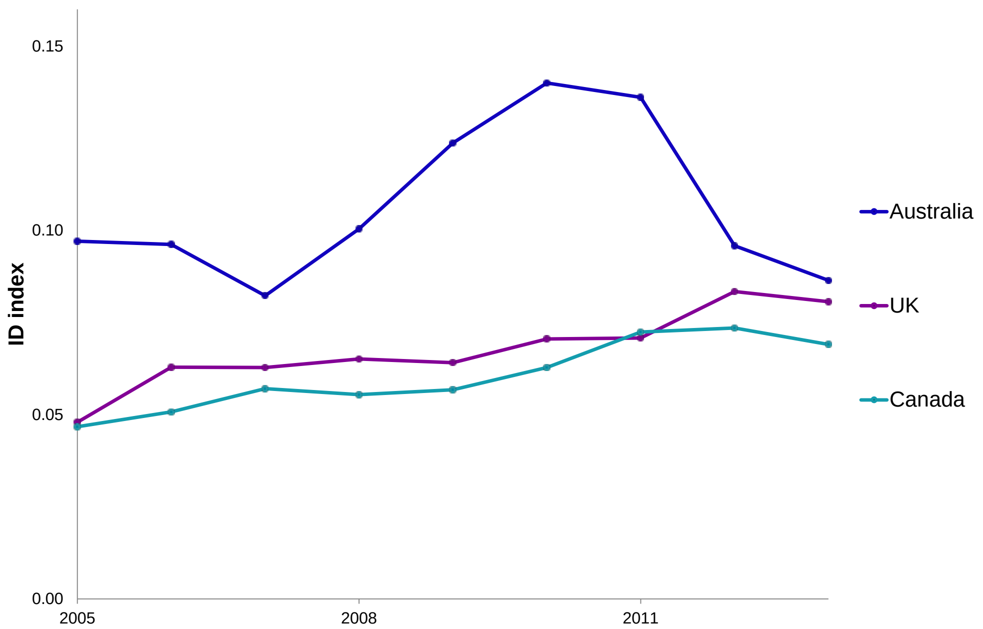


Figure D8. Biological sciences: index of interdisciplinarity in grant text data for Anglophone research economies. The data displayed here are three-year rolling windows for the average ID index for grants assigned to an FoR Group within the ANZSRC Division of Biological Sciences.



ANNEX E: Output multidisciplinarity - article addresses

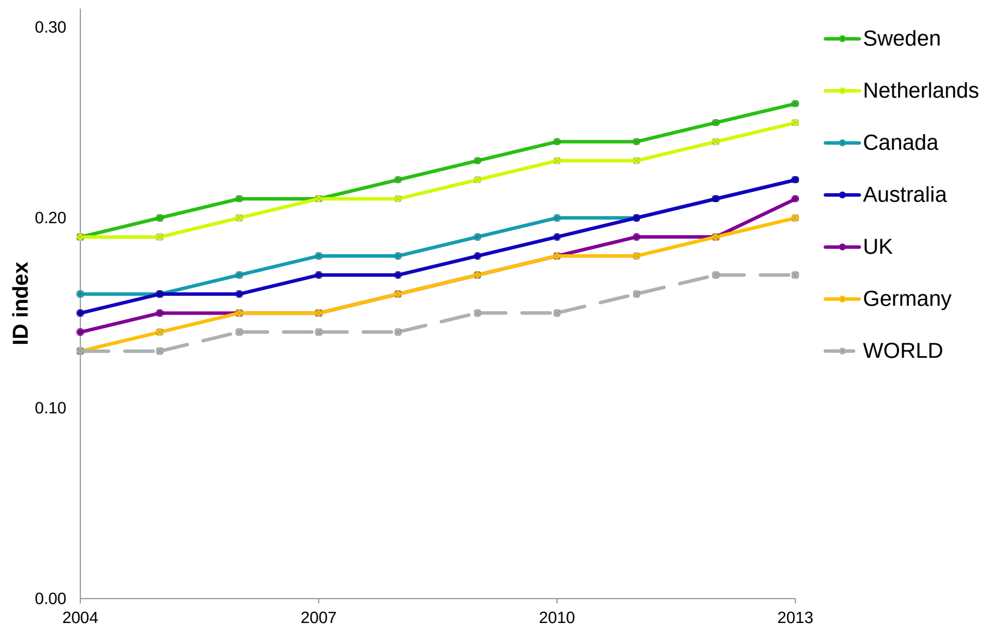
This Annex reviews an index of author addresses on journal articles. Annex F reviews an index of reference lists for the same articles.

SUMMARY. *The calculated values of an MD index based on author addresses are increasing globally, as is the average article address count and the volume of articles. The MD index is correlated with article volume at field level, and it is also higher for smaller countries. The UK has a lower MD index than the comparator countries but is above world average. For the UK and other countries, the MD index is higher in science and technology, particularly in biology, medicine and environment, than in social sciences and humanities.*

The average address count on journal articles has been increasing and it is higher for the natural sciences than for social sciences and humanities. There are more addresses on Netherlands and Swedish papers, but Australia and Canada have similar average address counts to the UK. There has historically been cultural diversity in the propensity for collaborative authorship between disciplines and between countries.

The MD index rises steadily with an almost linear trajectory for all countries. The UK has a lower average MD index than most other select countries, is similar to Germany and has a higher MD than the world average. The countries with persistently higher MD values among those analysed here are those with a higher average count of addresses per paper (Table C3).

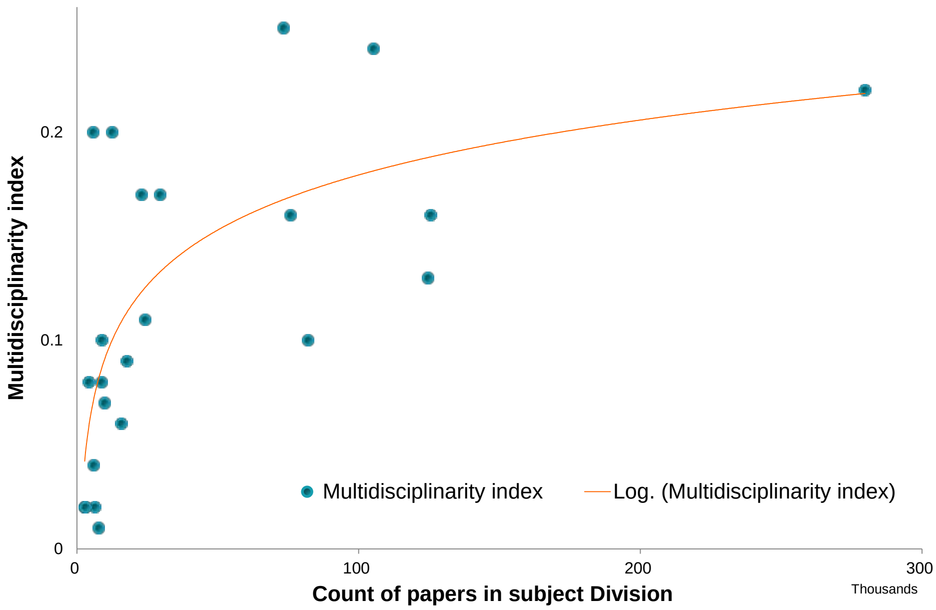
Figure E1. Average MD index (based on author addresses in articles indexed in Thomson Reuters Web of Science™*) for selected countries by year*



Although it is unsurprising that the address count is associated with the disciplinary spread of those addresses, it is desirable to distinguish between the effects of address number *per se* and their disparity. There is global growth in output volume and international collaboration, and most of the increase in national output is due to collaboration rather than domestic activity (Adams, 2013).

Figure E2 shows a second effect in the overall dataset: that MD is significantly positively correlated with sample size for global data. That it so say, the Divisions with a greater number of articles have the higher MD index and there is a (statistically significant) correlation.

Figure E2. Average MD index (based on author addresses) compared with numbers of articles by ANZSRC Division for global 2013 data. The variance explained by the logarithmic fit shown is r^2=0.47.



The volume of articles recorded by Thomson Reuters *Web of Science*™ in each field tends to rise over time. If the statistics suggest a correlated rise in article count and MD index then there is either a remarkably uniform increase in MD teams or a hitherto undescribed interaction between data volume and indexing. There are therefore three potentially interacting factors: the number of articles, the number of addresses on an article, and the MD index (which is calculated from the number and disparity of addresses).

The average MD index is generally higher for natural sciences (which have more addresses and a greater volume of articles) than for social sciences and humanities, again reflecting the average address count. In the next section (ANNEX F) the ID index calculated from reference lists for the same global source of articles shows an opposite trend with higher ID values in the social sciences and humanities.

There are smaller numbers of articles in the social science and humanities, which are less comprehensively indexed in Thomson Reuters *Web of Science*™, and the MD index values are typically less than 0.5. Change in MD index over the decade is extremely volatile, because of the smaller volume, so some of these data are omitted from the next figures for clarity.

To recap, these data are grouped by FoR at Division level but indexed at a finer granularity determined within the data. Any one article is associated with all the FoRs covered by its author addresses and may be in more than one aggregate group. What the analysis shows is the average MD index for articles that include any FoR as shown (e.g. articles for which at least one address is linked to Chemical Sciences but which may also have addresses for other fields).

The FoRs with the highest MD indices, which all end the analytical period with an index over 0.2, are Biological Sciences, Medical & health Sciences and Agriculture, Environmental and Earth Sciences, and Technology and Physical Sciences.

Both the UK and Germany have a rising MD index in all fields, in line with overall average MD index, with a generally rising volume of articles and with little change in rank order over the period.

Figure E3. UK data: MD index by ANZSRC Division (based on author addresses in articles indexed on Thomson Reuters Web of Science™). There is a similar increase for all fields.

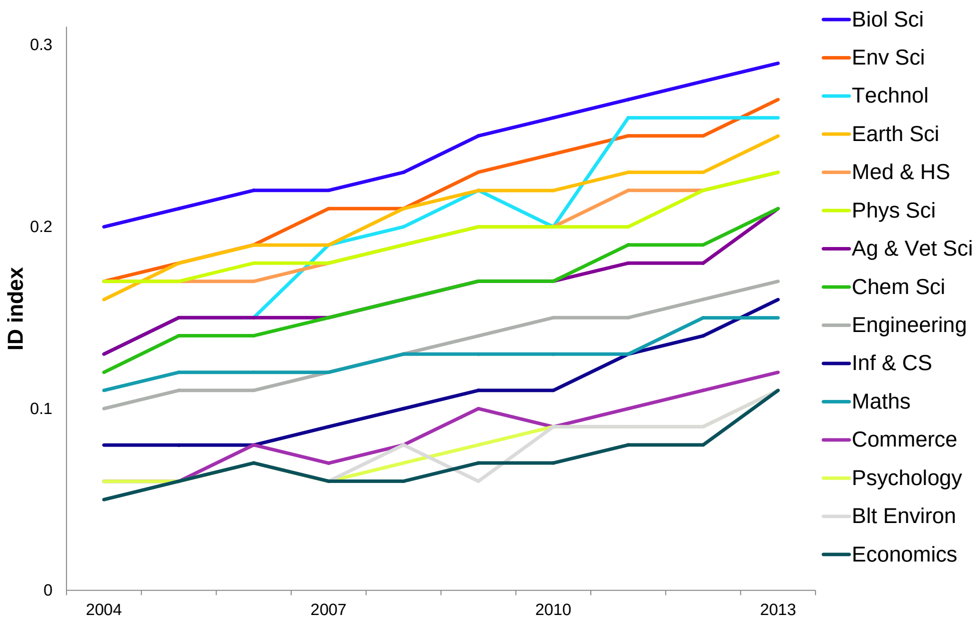
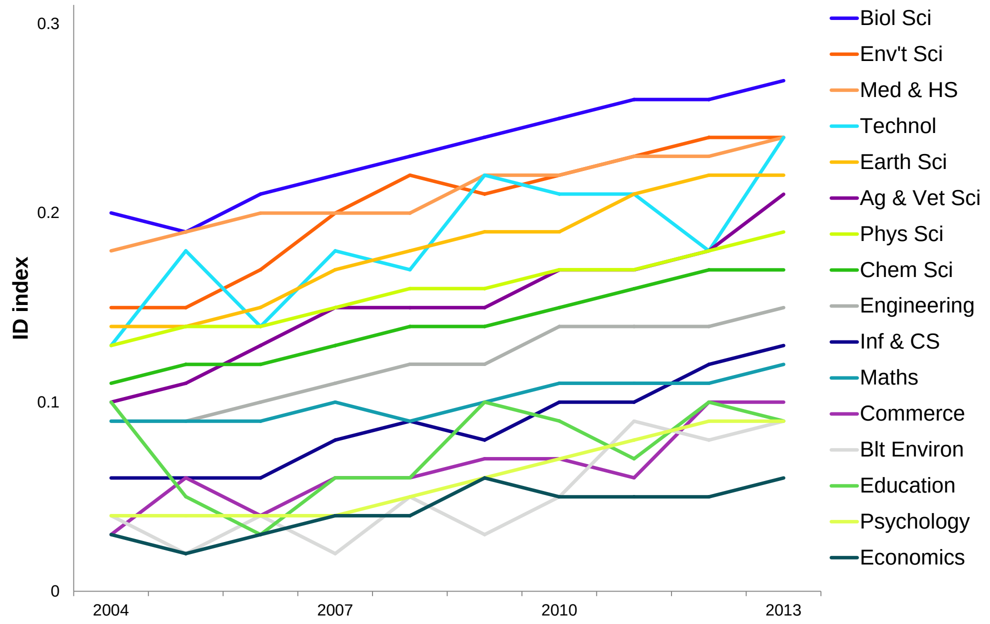


Figure E4. Germany data: MD index by ANZSRC Division (based on author addresses in articles indexed on Thomson Reuters Web of Science™). There is a similar increase for all fields.



ANNEX F: Output interdisciplinarity – article reference lists

SUMMARY. *The top 1% threshold used to take a sample of articles with sufficiently rich reference list for analysis is stringent, but marginal variations do not appear to undermine its validity. The fields with relatively more frequent high ID articles are generally those with a low MD index. There are relatively more high ID papers in recent years, and this trend is true for all countries. The UK's share is better than pro rata and has been maintained over the period. The UK's ID index is above world average and shows no marked trend compared to that average either at country or field level. There is no marked separation on ID index between natural and social sciences. The analysis for Germany shows a similar outcome.*

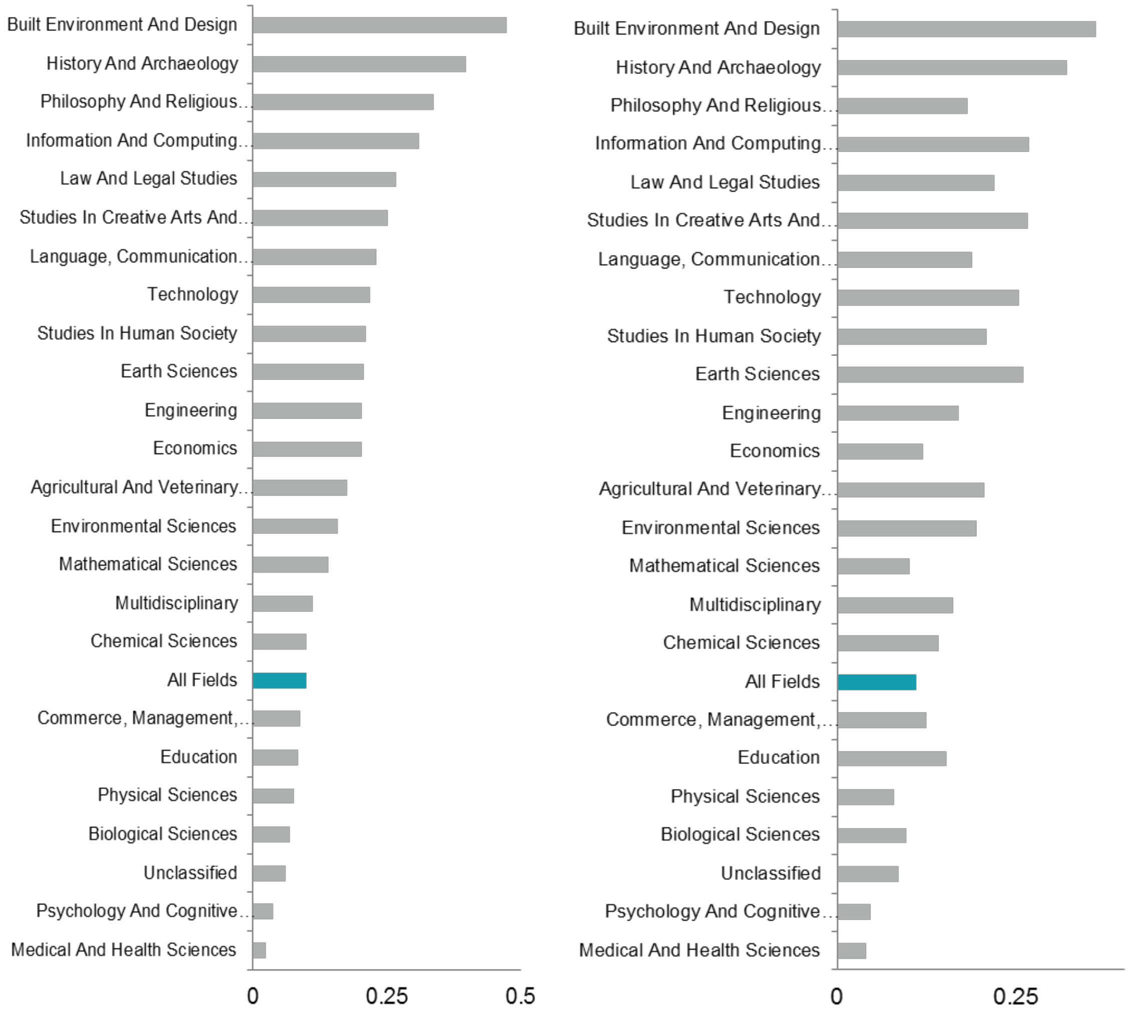
We need to examine two distinct features of interdisciplinarity (ID) as indexed through data on the disciplinary disparity and balance of article reference lists.

- What proportion of a country's papers fall in the global 10% most interdisciplinary among the global sample analysed? The question is about position and change relative to a world benchmark of 10%.
- What is the average ID index of the sample of papers that we analyse compared to a global average? The question is about position and change compared to a world benchmark of 1.0 (akin to citation indices normalised by year and field).

Many social science (e.g. Built Environment) and humanities (e.g. History and Archaeology) fields rank high on the ID index regardless of the details of the correction method whereas Mathematics falls in the middle and both Physical Sciences and Medical and Health Sciences rank at the low ID end (Figure F1). This ID rank sequence appears somewhat counterintuitive. The index is, at this field level, negatively correlated with the analysis of MD author addresses (above, where collaboration was lower [fewer addresses] in the Humanities). However, a similar analysis of references in Scopus has shown that in the humanities the breadth of knowledge integration can be diverse.

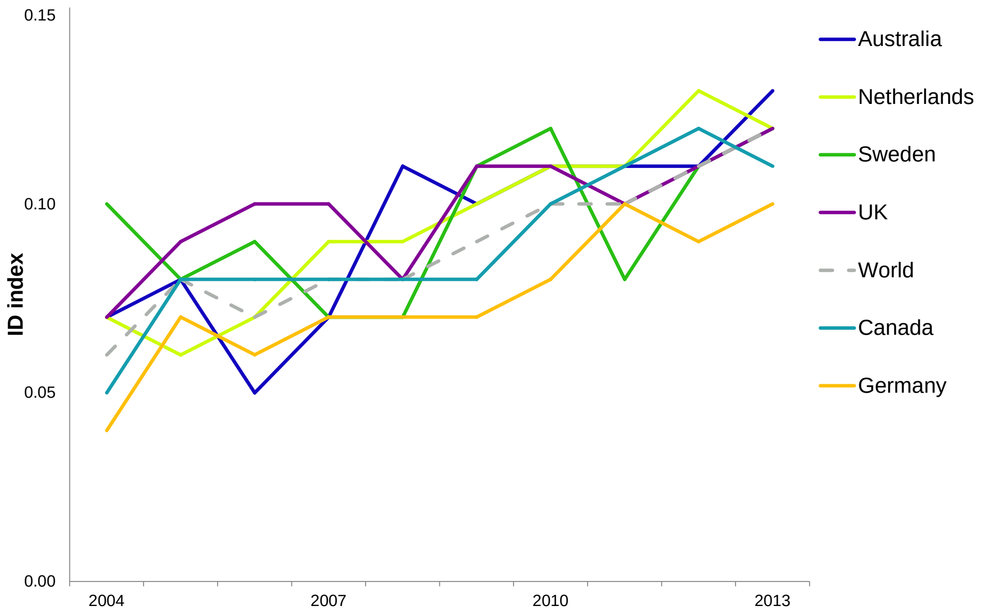
The values of ID indices may also be compared between countries and between fields within countries. For the global sample as a whole there is an increase in volume over the period, which means that a greater proportion of the global top 10% are in the most recent years and the volume increases by year.

Figure F1. Percentage of articles by FoR fall in the global 10% most interdisciplinary among (left) the 1% of papers with the largest number of classified references by FoR or (right) among the 20% of papers with the largest percentage of classified references (2004–2013)



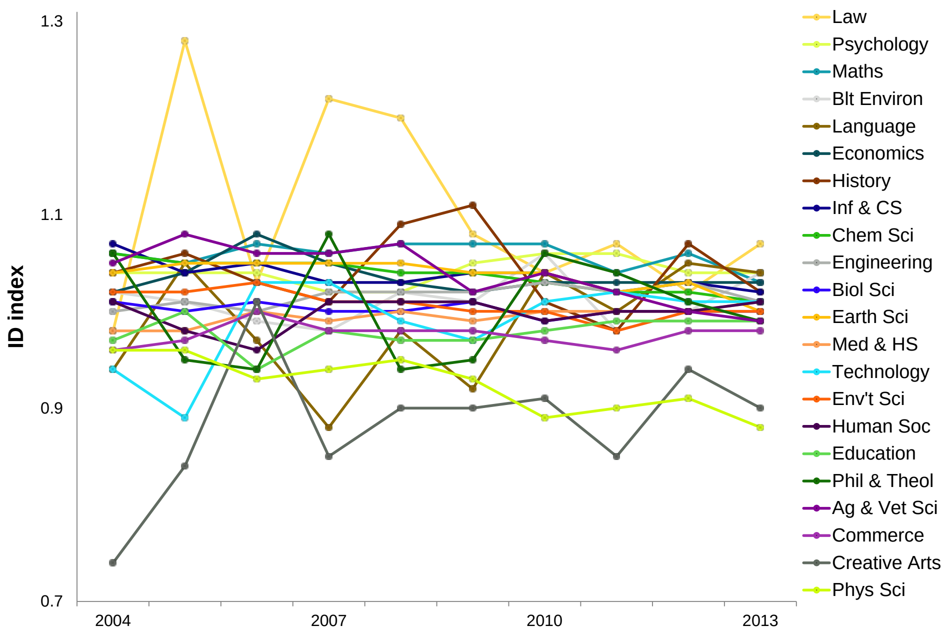
The UK percentage of papers in the overall global 10% increases over time and it consistently has a greater ID share than Germany. As with the MD analyses, the smaller countries have relatively more articles that meet the ID threshold criteria. (Figure F2)

Figure F2. Trends in the proportion of papers that fall in the 10% most interdisciplinary among the 1% of papers indexed on Thomson Reuters Web of Science™ with the largest number of classified references, 2004–2013.



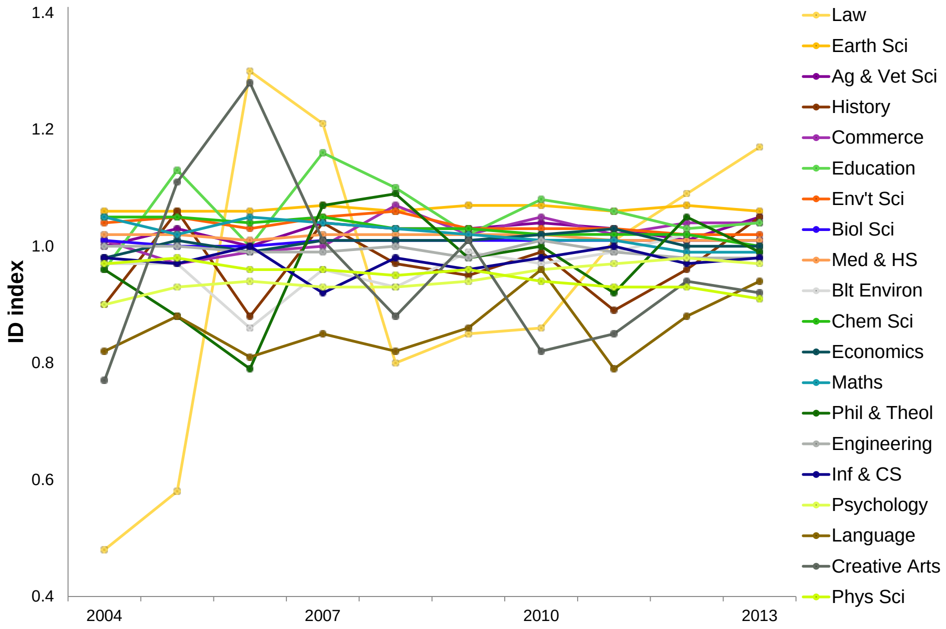
The global ID index is, of course, 1.0 in all years and by FoR. The UK average across all fields varies between 1 and 1.01 relative to that world benchmark. When the data are disaggregated by FoR then the ID indices for UK fields (Figure F3) group around the world average showing no clear trend and generally little variation, except for a declining index in Physics. It is difficult to discern any separation between UK science and social science fields in terms of the ID index.

Figure F3. UK data: trends in the ID index for analyses based on reference lists in papers indexed on Thomson Reuters Web of Science™ by year and ANZSRC Division. There is no clear temporal trend and values cluster around the world average (1.0).



For Germany (Figure F4), the picture is similar to the UK. ID index values group around the world average though with a slightly greater spread and annual variation.

Figure F4. Germany data: trends in the ID index for analyses based on reference lists in papers indexed on Thomson Reuters Web of Science™ by year and ANZSRC Division. There is no clear temporal trend and values cluster around the world average (1.0) although the variance is greater than for the UK.



ANNEX F: SUPPLEMENT - Comparison between multidisciplinarity of author addresses and interdisciplinarity of reference lists

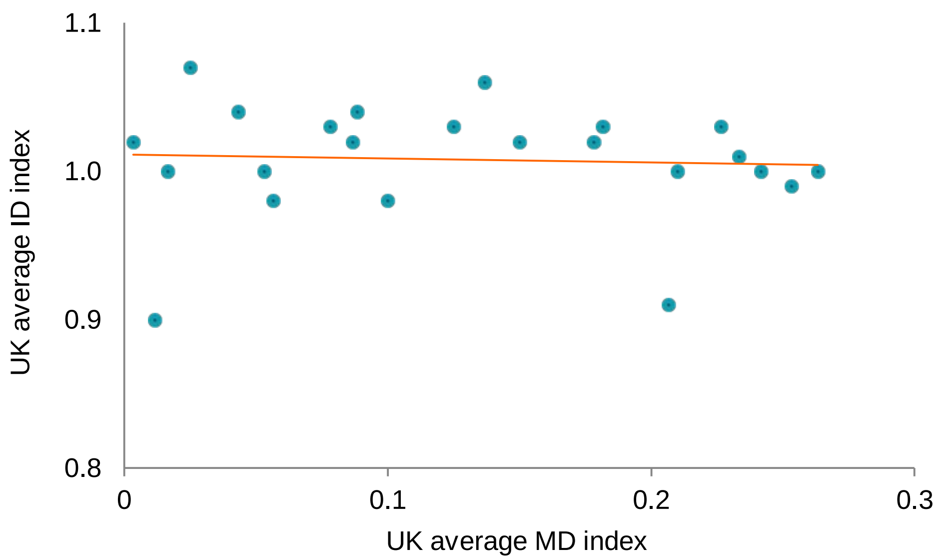
SUMMARY. *The MD (address) index can be compared with the percentage of articles that fall in the global top-10% (ID by reference list) using the data for the most recent year. For the global data, the outcome is not statistically significant (r^2 = 0.28, 0.1>P>0.05). For the UK, the trend is statistically non-significant.*

The MD address analysis and the ID reference list analysis have been applied to the same set of journal articles from the same commercial source (Thomson Reuters *Web of Science*™). This is not an analysis on an article-by-article level but it does provide a general overview of the outcomes at FoR (Division) level. There is no functional reason why the two parameters should have to be mutually dependent, but if the analytical outcomes are inconsistent then this tells us that they are not reflecting a common characteristic of the research activity.

For the global data there is a slight negative association, so on average fields that have higher MD author teams have lower ID reference lists.

For the UK data, the trend is not statistically significant and the data are essentially a cloud. There are two outlier values with exceptionally low ID index values, in Creative Arts and Physical Sciences. There is no sound justification for excluding these, but if the correlation is calculated without them then the negative trend is of similar (slight negative) statistical significance to the global data.

Figure F5 - UK articles (2008-13): correlation for data aggregated at the ANZSCR FoR Division level between the average MD index and ID index (r^2=0.003).



The outcome of this comparison means that we cannot conclude that MD teams and ID reference lists are mutually coherent indicators of the general level of interdisciplinarity in the underlying research. Thus, the analyses of Thomson Reuters *Web of Science*™ journal article data suggest that the disciplinary make-up of teams and reference lists is at best unrelated and may point in opposite directions for research management.

This outcome also raises an important general *caveat* about the interpretation of journal article data if used as proxy indicators of research activity as opposed to indicators of research achievement.

ANNEX G: Output interdisciplinarity – article abstracts

The MD-address and ID-reference analyses for Thomson Reuters *Web of Science*™ journal articles produced contradictory results (ANNEX E and F, especially Figure F5). Although these may be valid indicators of the extent to which teams are multidisciplinary or referenced literature is interdisciplinary, they evidently do not provide a consistent indicator for the research articles, and thus also not for the research from which the article arose.

Text analysis of article abstracts would provide an indicator to compare with both these article analyses and with the text analysis of grant abstracts (ANNEX D). The potential benefit of text analysis is that it draws on descriptive information given by the researchers for the identification of disciplinary varieties rather than drawing on potentially mis-assigned metadata. Addresses may not accurately identify the researcher's discipline (e.g. mathematicians working in other science or social science units) and reference lists may be conditioned by editorial and journal expectations.

Because the full text of article summaries was required, the analysis was limited to the article set accessible through PubMed. Consequently, it is not feasible to carry out a complete disciplinary spectrum and a focus on publications from medical, health and supporting bioscience areas is to be expected. As noted in ANNEX B, this means that when non-medical disciplines such as Law are discovered they are very likely to be in an interdisciplinary context. However, the PubMed data provided a 25 year series which gave a longer perspective on the trajectory of ID than in other data.

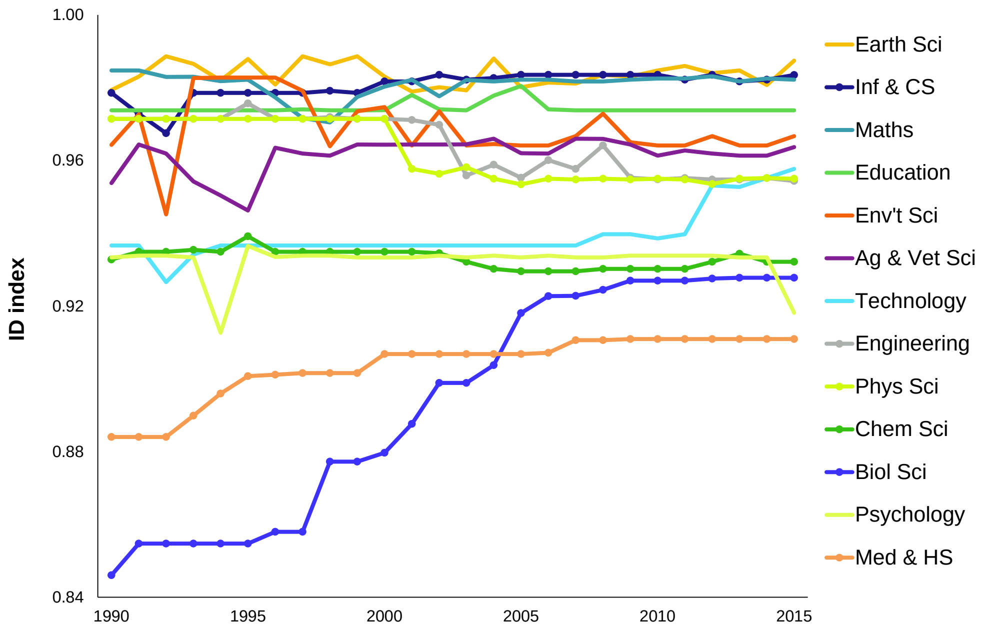
Calculated ID values at the article level are highly skewed, so the average is not informative. To address this skew, the critical values displayed in the analyses are the 95th percentile for each variety (FoR Division or Group).

Interdisciplinarity at Division level

The text-based ID index is relatively high for many disciplines at the broader ANZSRC Division level, which is probably due to the partial coverage of the PubMed data. The lowest average ID values are in Biological Sciences and in Medical and Health Sciences, and Psychology and Technology have slightly lower ID than the other Divisions. (Figure G1)

The ID of the core bio-medical divisions rises over the period from 1990 to 2015. They may have started at a lower ID level for two reasons: first, because they are core to this dataset and therefore most likely to produce less ID material in this context; second, because these are very broad research categories in any database and in the early 1990s research in these areas may have been contained within this group of fields. The rise over the period is informative because these fields are not part of a uniform response across all data.

Figure G1. Interdisciplinarity index for text-based analysis of PubMed article summaries, grouped at ANZSRC Division level.



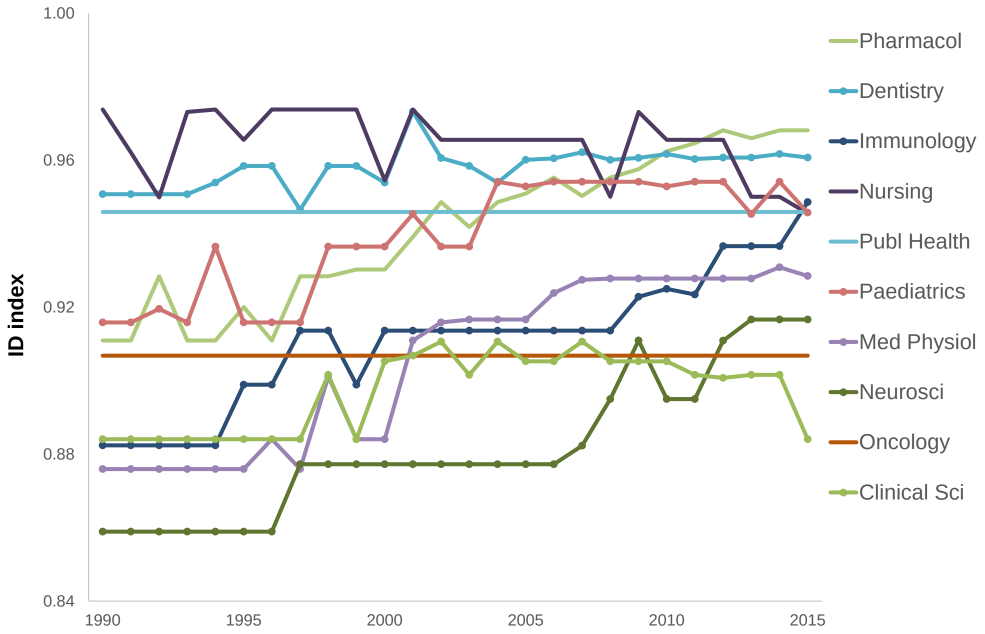
There are sufficient data for a more detailed analysis of the variations in the ID index at the finer-grained Group level within Medical and Health Sciences and Biological Sciences.

Interdisciplinarity at Group level

Within Medical and Health Sciences, it is evident that some fields are more ID throughout the period while it is just a few fields (with relatively large volumes of research outputs) that have contributed to the overall rise in the ID index for the Division.

Clinical Sciences is one field that has a rising ID, while the other contributors are Neurosciences (which starts lowest and picks up particularly in the period around 2008), Immunology and Medical Physiology. Another field of interest is Pharmacology, which already has an ID above 0.9 in 1990 but rises past other fields to become one of the highest in 2015. (Figure G2)

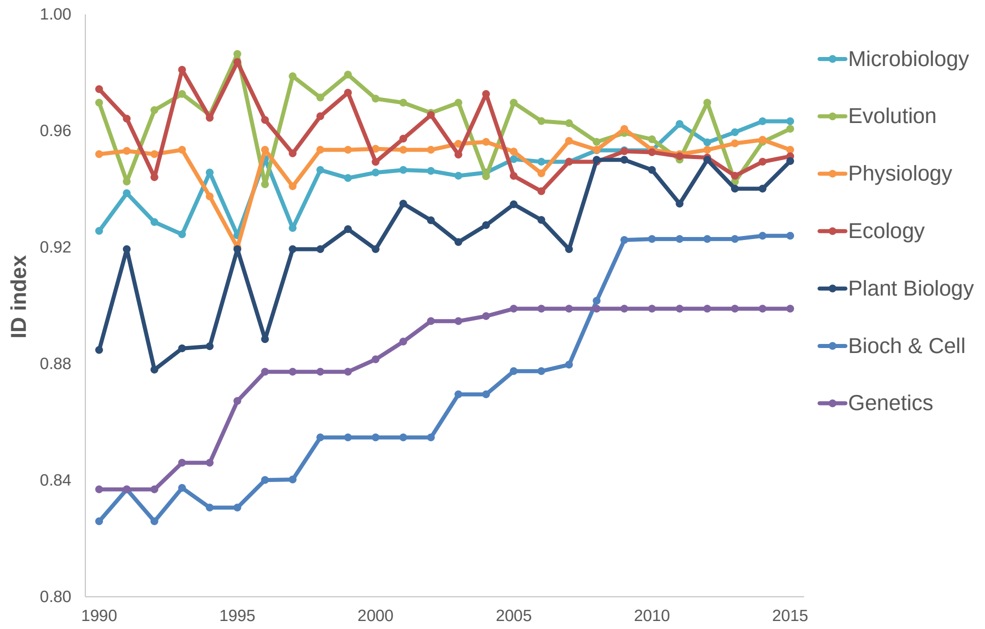
Figure G2. Interdisciplinarity index for text-based analysis of PubMed article summaries, at Group level within ANZSRC Division 11 for Medical and Health Sciences.



Within Biological Sciences, most of the rise in the Division's ID index is driven by progressively increasing ID metrics in Biochemistry and Cell biology and in Genetics. Plant Biology also starts slightly below the other Groups and increases in ID to reach the general level. (Figure G3)

This change in ID index for Biochemistry/Genetics may be a reflection of the extent to which these two fields have become pervasive throughout the life sciences. In 1990 they were still evolving some of the core technologies that have contributed to that engagement and so they would, as large fields, have tended to be less ID and perhaps more introspective. As the technology and the significance of genomics and proteomics became evident, their shift to higher ID would have been expected.

Figure G3. Interdisciplinarity index for text-based analysis of PubMed article summaries, at Group level within ANZSRC Division 6 for Biological Sciences.

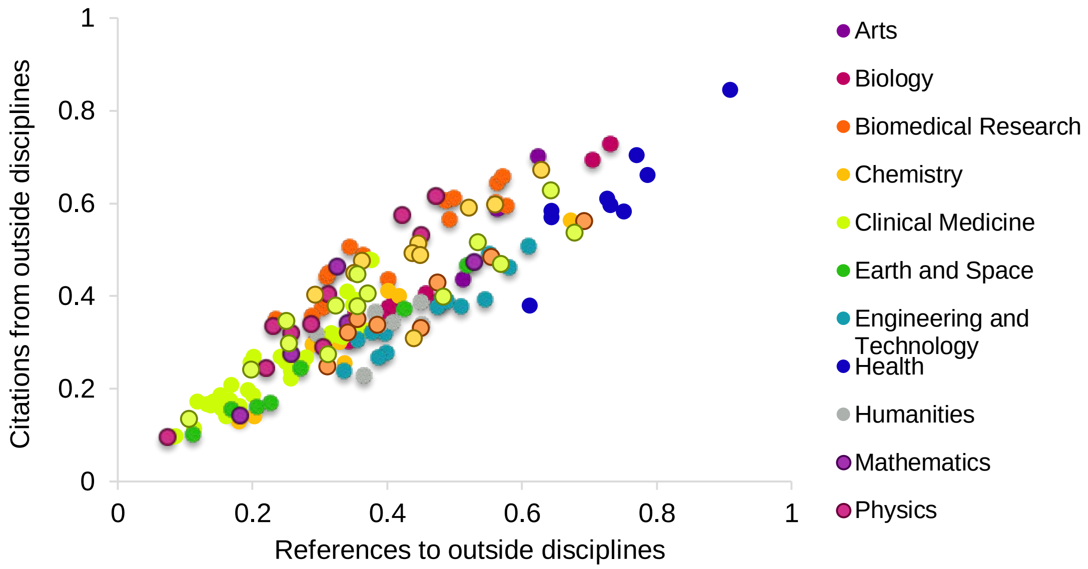


The shifts in ID and the differences between fields appear to be consonant with what would have been expected. The largest Groups in these Divisions has lower ID indices, comparable to the ID differences for smaller and large countries. These fields were growing because of the significant technologies they offered. As these matured the fields naturally became engaged with other Groups to which the technology was applicable. The narrative indicated by the text-based analysis is coherent with changes in the underlying research activity.

ANNEX H: Output interdisciplinarity – analysis in *Nature*

Nature recently ran a supplementary feature on interdisciplinary research (Nature, 17 Sept 2015). This included a graphic illustrating the correlation between the disciplinary spread of cited and citing references using bibliometric data collated by Vincent Lariviere (Univ Montreal) and Cassidy Sugimoto (Indiana Univ).

Figure H1. A measure of interdisciplinarity based on the citation flow of references to/from a journal article.



This follows an NSF categorical system and is not quite comparable to that used by ANZSRC FoRs, but it suggests a potentially important variance hidden in other grouped data. In this analysis, Clinical Medicine (low ID) and Health (high ID) have been split by NSF into separate categories and appear in quite different parts of the graph. For the ANZSRC, Medicine and Health is a single category.

Other fields broadly appear to match expectations. It would be surprising if there is major divergence since the basket of journals must be fairly similar and the cited references ought therefore to match for the articles. However, the citing references offer a further (and apparently significantly positively correlated) dimension.

The *Nature* feature also looked at country averages and found the UK (9.1%) to be more interdisciplinary than Germany (8.5%) but both to be less so than other comparator nations, which included USA and Japan (both 9.7%) and the BRICK[6] and other emergent economies (10-13%).

The meaning of the country and field differences is unclear: the value of the analysis here is in comparison to other methods and outcomes studied in the report.

[6] BRICK: Brazil, Russia, India, China, (South) Korea

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