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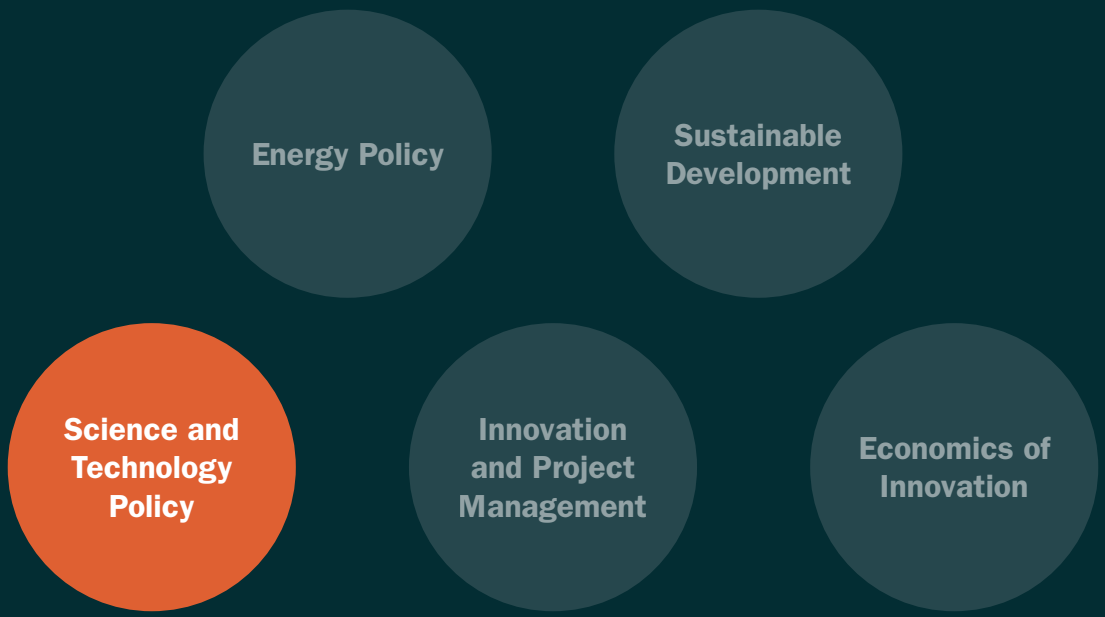

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DARE to be different? Applying diversity indicators to the evaluation of collaborative research projects

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Abstract

Growth in collaborative research raises challenges for those tasked with research evaluation, particularly in situations where outcomes are slow to emerge. This article presents the 'Diversity Approach to Research Evaluation' (DARE) as a novel way to assess how researchers, engaged in knowledge creation and application, work together as teams. DARE provides two important insights: Firstly it reveals the differences in background and experience between individual team members that can make research collaboration both valuable and challenging; secondly, DARE provides early insights into how these teams are working together. DARE achieves these insights by analysing team diversity and cohesiveness in five dimensions, building on Boschma's multidimensional concept of proximity. The method we propose combines narratives, maps, and indicators and is broadly applicable to the study of research collaboration. The article introduces the DARE method and pilots a proof-of-concept operationalisation through the study of two grant-funded biomedical research projects led by researchers in the UK. Suggestions for further development of the approach are discussed.

1. Introduction

This article presents a novel approach to the assessment of how teams of diverse individuals collaborate during knowledge production and application processes. The Diversity Approach to Research Evaluation (DARE) generates insights into collaborative processes using a combination of *narratives, maps and indicators*. The method operationalises a previously elaborated conceptual framework that defines the different kinds of diversity which need to be bridged during knowledge intensive collaborations (Molas-Gallart et al. 2016). The approach enables the study of the diversity of individuals engaged in collaborations and reveals how such diversities are bridged though the collaborative processes. Diversity is defined as a property of a system containing elements apportioned to different categories (Stirling 2007). For example, if a team of collaborating individuals all work in the same location their geographic diversity is lower than that of a team where individuals

are distributed across different locations. It has long been recognised that diversity in characteristics such as ethnicity and age within a team can have an influence on performance, suggesting *multiple dimensions* may be analytically relevant in explaining team creativity (McLeod et al. 1996). More recently, Boschma (2005) has proposed how several other dimensions such as geography and institutional context may influence knowledge intensive collaborations. Furthermore, there is a long tradition of work suggesting diverse individuals need to work together to facilitate research on increasingly complex problems and for knowledge translation for innovation to occur (Laudel, 2001; Joly et al. 2015). DARE seeks to build on these studies by providing a general approach for analysis of diversity in research collaborations, in multiple dimensions, in the context of a long-run trend in knowledge production in science and technology for increased collaboration (Katz & Martin, 1997; Wuchty et al. 2007).

Teamwork provides creative opportunities by bringing together diverse individuals with different ideas, expertise and resources, yet it also is associated with high costs related to coordination and communication (Cummings & Kiesler 2007; Guimerà et al. 2005; Wuchty et al. 2007). Such difficulties can make the accomplishment of goals through collaborative research projects a substantial challenge and even lead some to question the effectiveness of such research investments (Cooke & Hilton 2015; Stokols et al. 2008). There is now a recognised need for new methods that can provide understanding, at a micro level, of how collaborative research leads to valued outcomes and impacts (Cooke & Hilton 2015; MRC 2012; Oancea et al. 2017).

The challenge of evaluating the contributions of interventions that take place a long way upstream from the potential societal impacts is not unique to research policy. It is encountered in other policy fields, where it is arguably inadequate to attribute impacts to specific policy measures and upstream activities (Smutylo 2001).

One of the ways in which evaluators have responded to this challenge is by focusing their attention on the characteristics of early stage knowledge generation and application processes, and the intermediate outcomes they generate. A stream of research evaluation practice has emerged that focuses on processes (rather than outputs and impacts), for instance, the 'productive interactions' between researchers and non-academic stakeholders and how these are conducive to the generation of impacts (Molas-Gallart & Tang, 2011; Spaapen & van Drooge, 2011, Oancea et al. 2017). The approach introduced in this article is located in this strand of research evaluation. We build on the notion that the potential effects of research investments depend on the interactions built among individuals during knowledge production or transfer.

This stream of evaluation practice is distinct from, and provides an additional perspective to, other approaches that analyse the knowledge generation and application processes by using an events-based approach to track progress in research or 'payback' of investments (Buxton & Hanney 1996; Trochim et al. 2011). Such approaches tell us little about how the different participants involved in the process have contributed to the outcomes and impacts that have been generated over time. To assess the contribution of a research project / innovation programme, or to improve support for research, it is necessary to understand whether and how diverse participants work together.

This article advocates the study of interactions between researchers and other participants established during research collaborations as these interactions are the necessary and observable precursors of knowledge creation and application. Such interactions can be challenging because they require the coming together of diverse participants who are members of different organisations and disciplines, and are motivated by different incentives that are potentially not aligned (Boschma 2005; Cooke & Hilton 2015; Heinze & Kuhlmann 2008; Newell et al. 2008; Swan et al. 2007, 2010). Whether

and how these differences are bridged becomes a crucial evaluation question because if they are not addressed there is a risk that new knowledge formation will be impeded (Boschma 2005). In turn, the ability to study collaboration one dimension at a time, layer by layer, as well as combinations of dimensions, can support fundamental understanding of research collaboration as well as formative evaluation processes. The contribution of each dimension to the whole can be studied, aiding understanding of the links between patterns of interaction to desirable outcomes in research projects or programmes.

DARE provides a detailed basis for analysis of research collaborations, and in particular, can be used for longitudinal comparisons of particular relevance for evaluation studies. The next section introduces the concepts of diversity and cohesiveness, which are key components of DARE. The methods used in the application of these concepts are explained in Section 3. Section 4 presents two illustrations of how the approach can be used to study specific instances of research collaboration. The illustrations are presented as a 'proof of concept' that DARE can provide an informative description of collaborations, rather than with the aim of advancing theory. Section 5 discusses the potential applications of DARE, and the practical and technical limitations apparent from its operationalisation in its present form. Future opportunities for development of the method are also outlined.

2. Conceptualising diversity in research collaborations

This section introduces the conceptual framework used in DARE for the study of interactions that occur in research collaborations. In this method, diversity can be characterised in multiple dimensions. DARE is compatible with a wide range of possible dimensions of diversity. Indeed, it is a key tenet of the method that it can be used to integrate and distinguish between different forms of diversity in research collaborations, so as to provide a series of individually insightful perspectives on the same research effort. In this article we use five dimensions introduced in a seminal article by the economic geographer Ron Boschma: *cognitive, organisational, social, institutional* and *geographic* (these are set out in Table 1). Boschma proposed that these dimensions of distance (proximity) influence interactive learning and innovation (Boschma, 2005).[1]

Molas-Gallart et al. (2016) draw on Boschma's framework and further propose that research investments seeking to foster collaboration should be assessed across these five dimensions as each can potentially highlight a different type of challenge to be overcome by the participants.

Participants can be closer in some dimensions, potentially presenting lower barriers to working together while at the same time being more distant in others. More distance suggests a greater bridging effort to overcome gaps, but implies greater potential for bringing together more disparate knowledge.[2] The ability to observe *how much* distance is involved in a collaboration can be seen as a first step to understanding the impact of distances on collaborations and their outcomes.

[1] While Boschma's work conceptualises these dimensions in terms of 'proximity', here the term 'distance' is used to emphasise the gaps that are bridged during collaborations, although proximity and distance can simply be regarded as negatively correlated.

[2] Boschma emphasises that both too much and too little proximity between collaborating individuals can be detrimental to innovation and learning processes (Boschma 2005). Too little proximity makes it difficult to engage in interactive learning, and therefore we should not take a normative position that a network displaying long distances among its nodes is always "better".

The conceptualisation by Boschma (2005) characterises relations between individuals. Many studies that follow Boschma's framework characterise and analyse distances between pairs of individuals (dyadic interactions, e.g. Hardeman et al. 2014; Ponds et al. 2007). While distance (proximity) can be used when discussing relationships between pairs of individuals (dyadic interactions), this concept is not applicable to the study of teams. What is required for the study of team dynamics is to characterise the network of interactions of the ensemble of participants in order to understand how they interact collectively. To this end, we will use the constructs of diversity and cohesiveness previously used to map 'knowledge integration' in interdisciplinary research (Ràfols 2014; Ràfols et al. 2012). We propose to use diversity and cohesiveness to describe the differences between individuals working together in teams and the extent to which they work together. These concepts are operationalised in the maps and indicators described below.

Table 1: Five distances that influence collaborative knowledge creation, following Boschma (2005)

Geographic distance	Geographic distance refers to spatial separation between actors. Spatial co-location facilitates the exchange of knowledge particularly in cases where knowledge is complex or difficult to transfer (such as tacit knowledge).
Cognitive distance	Cognitive distance refers to the extent to which actors differ in their knowledge bases. Some degree of cognitive similarity (i.e. a shared conceptual lexicon or agreed system of problem solving) is a prerequisite for interactive learning, as it facilitates communication.
Social distance	Social distance refers to the extent of relations between actors, generally built on familiarity, friendship and kinship. Where such relationships are close they facilitate empathy, communication and coordination.
Organisational distance	Organisational distance refers to the separation of individuals by hierarchical structures, whether individuals are members of different parts of the same organisation or members of different hierarchies in separate organisations.
Institutional distance	The institutional dimension refers to the norms, rules and values that influence how actors behave. Large institutional distances may impose serious impediments to fruitful interactions if interacting actors respond to different, even potentially conflicting, sets of incentives or values.

Another key tenet of DARE is the important role of *cohesiveness* amongst those involved in a collaboration. Working relationships between distant individuals may be necessary but also challenging to establish and maintain. An important objective to foster research collaboration may therefore be to generate interactions between diverse individuals. When these interactions take place, the network then increases its cohesiveness. A given initiative can increase cohesiveness by establishing or strengthening links between distant participants.

DARE analyses collaborations in different dimensions, which requires individual participants to be assigned to relevant categories for each dimension and links between individuals to be recorded (see Figure 1). The resulting diversity and cohesiveness measures are anticipated to vary by dimension and over time. This dynamic description of collaboration has, so far, been missing in evaluation of research, as critiqued by Balland et al. (2014).

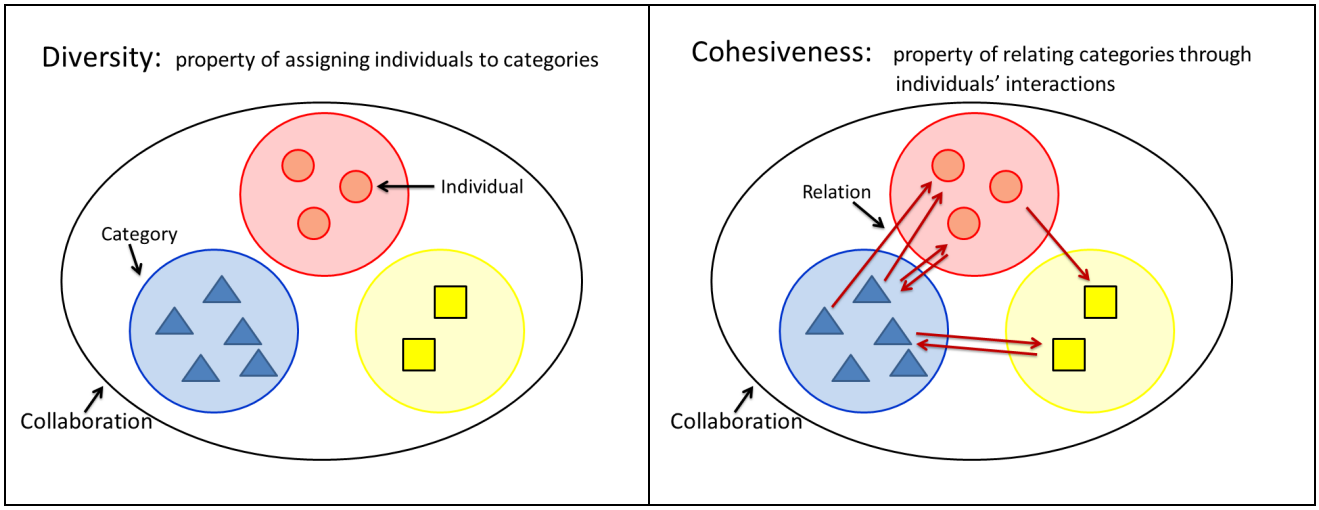

Figure 1: Illustration of diversity and cohesiveness of a collaboration for a given analytical dimension. Adapted from Ràfols (2014)

Measuring diversity and cohesiveness

Building on contributions by Stirling (2007) and Ràfols (2014), Box 1 describes the formulae used in DARE to measure diversity and cohesiveness. These form the basis to produce the network maps and indicators used in this article. A key difference between the proposed indicators and conventional network analysis (e.g. as described in Wasserman & Faust 1994) is that DARE is concerned with network structure rather than solely node attributes. The diversity indicators used here rely on individuals' attributes, while the cohesiveness indicators rely on both individuals' attributes and the strength of individuals' interactions.

Diversity

The diversity index used by Stirling (2007) and Ràfols (2014) provides an indicator describing how individuals are distributed across categories, accounting for the distances across these categories. Box 1(a) shows in mathematical terms the formula from Stirling (2007) where the distance (δ_{kl}) between individual k and individual l is defined as the distance (d_{ij}) between category i of individual k, and category j of individual l, while those in the same category are assigned a zero distance between them. In DARE, distances are assigned between individuals rather than categories, so as to produce a more fine-grained description (e.g. distance can be defined as a continuous variable, rather than a distance between each pair of categories considered). This refinement is expressed in the second formula in Box 1(a). It is this second formula that is applied in DARE.

Cohesiveness

In previous work, cohesiveness measured the intensity of interactions between categories (Ràfols, 2014), while taking into account the distances between these categories.[3] The distance implies difficulty to interact between individuals in different categories, but also the potential to establish access to complementary experience.

[3] Ràfols (2014) (as well as related previous work) used the term *coherence*. Here we use *cohesiveness*, since it portrays better the notion of efforts to link or relate disparate expertise without necessarily suggesting the building of a logical or unified whole. We thank Richard Woolley and Taran Thune for discussions on this point within the OSIRIS Project (http://www.sv.uio.no/tik/english/research/projects/osiris/).

In keeping with the diversity indicator above, the cohesiveness indicator presented here considers the interactions between pairs of individuals (rather than categories) taking into account the distance between them in a given dimension. Box 1 (b) describes mathematically how cohesiveness is expressed both at the level of categories (as in Ràfols, 2014) and at the individual level (in DARE) using the distance δ_{kl} that these interactions span.

A shortcoming of the cohesiveness measure resulting from the formulation in box 1(b) is that the measure is not bounded (unlike diversity which is expressed as a value between 0-1). This may mean that high and low values cannot be discerned without comparators. The cohesiveness can be expected to increase as team size and diversity increases, even in the absence of links between distant categories. In order to recognise the establishment of links across more distant categories, a distinct normalised indicator is proposed, namely, 'mean distance bridged', expressed in Box 1(c). The mean distance bridged represents the average distance across which individuals have interacted. The mean distance bridged can be interpreted in conjunction with the diversity indicator; if it is higher than the diversity indicator, this means that within this collaboration, individuals have formed more links with team members in distant categories than in closer categories.

The cohesiveness indicator can be used at two or more distinct points in time to show the extent of the links created during a given research collaboration. By providing an account of the cohesiveness changes, one can understand the specific efforts undertaken to bridge the distances, which in turn can provide an indication of the additionality of the project.

Box 1: Mathematical operationalisation of diversity and cohesiveness

a) Diversity index (left: in terms of categories; right: in terms of individuals)

$$\sum_{i,j} p_i p_j d_{ij} \Leftrightarrow \sum_{k,l} \frac{1}{n^2} \delta_{kl}$$

b) Cohesiveness (left: in terms of categories; right: in terms of individuals)

$$\sum_{i,j} i_{ij} d_{ij} \Leftrightarrow \sum_{k,l} \iota_{kl} \delta_{kl}$$

c) Mean distance bridged (Cohesiveness/Sum of intensities of interactions) (left: in terms of categories; right: in terms of individuals)

$$\frac{\sum_{i,j=1}^{n} i_{i,j}\, d_{ij}}{\sum_{i,j=1}^{n} i_{i,j}} \Leftrightarrow \sum_{i,j=1}^{n} p_{i,j}\, d_{ij} \Leftrightarrow \sum_{k,l=1}^{n} p_{k,l}\, \delta_{kl}$$

In the above formulae:
p_i is the proportion of individuals in category i
$d_{i,j}$ is the distance between categories i and j
n is the number of individuals.

δ_{kl} is the distance between the individual k and the individual l.
$i_{i,j}$ is the intensity of the interaction between the category i and category j
ι_{kl} is the intensity of the interaction between the individual k and the individual l.

$p_{i,j}$ is the proportion of the intensities of interactions between categories i, j
$p_{k,l}$ is the proportion of interactions between individuals k and l.

The following section details how one moves from these mathematical formulae to empirical measures, and discusses difficulties or limitations encountered when applying these to practical examples.

3. Methods for applying diversity and cohesiveness

This section presents the methods used for the DARE proof of concept, starting with the rationale justifying the selection of the illustrative cases, followed by a discussion of data collection and analysis.

Sample selection

In keeping with prior work (Molas-Gallart et al. 2016), this article provides a step towards demonstrating the versatility of DARE through application within two examples. These have been selected deliberately to provide a contrast with each other in ways that DARE can distinguish. Thus, the cases vary substantially in the five dimensions defined in Table 1, as well as in other regards such as team size and funding duration. By selecting contrasting cases it is possible to show how DARE can help to distinguish between the characteristics and structures of research collaborations.

The two examples are both grant funded projects that focus on 'translation' of biomedical research results into health-related applications. This emphasis on translation was chosen because this is an area where it was anticipated that research collaborations would involve diverse teams and where it has also been suggested that new evaluation approaches are required (Molas-Gallart et al. 2016).

Case 1 ('Biomarker analysis platform') involves a small team working across two organisations in the same country, and spanning the divide between public and private sectors. This provides a window into university-industry collaboration, itself a topic of considerable of academic and policy interest (Bruneel et al. 2010; Perkmann et al. 2013; Thune 2009). Key individuals in the project team shared social links prior to the project and most of the researchers involved shared their field of interest (oncology) prior to the project outset.

Case 2 ('Neglected disease epidemiology') involves a larger team of researchers, working across many more organisations, and spanning several low and high-income countries. This project brought together researchers from a range disciplines spanning the biomedical and geosciences. The organisations involved were all either part of the public sector or not-for-profit.[4]

The selection of research projects as the unit of analysis was motivated by the clear definition of the research collaboration with defined focus, identified team members, and a plan of activities, all provisionally discussed in a research proposal (which was accessed for the DARE analysis). These projects also had clear start dates and project durations, providing the opportunity to analyse changes occurring after the start of the project.

[4] This case was volunteered by a co-author of this article. Since the focus of this article is merely a demonstration of the DARE approach (and not a formal evaluation of the performance of the teams in the cases studied) this selection is not deemed to present any conflict of interest by the authors.

Data collection

As stated above, DARE relies on three elements: narratives, maps, and indicators. Each of these have a role in providing an understanding of how individuals interact during research collaborations. Narratives provide contextual information on the interactions, including details of the challenges of knowledge production, as well as observations on the project that may be necessary to make sense of the maps and indicators. Maps provide a basis for intuitive insights about the diversities and changes in cohesiveness that occur during the collaboration. Finally, indicators give a synthetic insight and an aggregate indication of the extent of changes in interactions. These different ways of presenting data provide complementary perspectives, explored together in the results section. For each of these analytical elements the main focus for data collection was interviews with project team members.

For both cases, the analysis started with an invitation to the project's Principal Investigator (PI) for an interview and a request to obtain a copy of the project proposal. In each case, initial discussion with the PI revealed changes to the staffing of the team between submission of the funding application and commencement of the award as well as revealing informal links that broadened the collaboration.

In each case, face-to-face interviews were conducted with the PI and a post-doctoral researcher who was core to the project team. Interviews were then conducted by telephone with three further researchers for Case 1 and two for Case 2. Only a small proportion of the researchers involved in each project were interviewed. The maps and indicators used in DARE rely on team members recalling and disclosing their collaborative links. Although the optimal situation would be to have all researchers involved in a project report their interactions, when research teams are large this is not practical. Instead, a selective approach was used to achieve some triangulation without becoming overly burdensome for the team being studied. When sampling interviewees from a wider network in this way, it is important to start with those best placed to provide a comprehensive overview, and then move to those involved in smaller independent sub-groups.

Interviews were recorded for accuracy, with the agreement of interviewees. The names of all team members used in this article are pseudonyms in order to preserve anonymity. The research protocol was subject to ethical review and approved by C-REC, the appropriate institutional-level committee at the University of Sussex (Ref. ER/FL49/1).

Data gathering: using sketch maps as an interview aid

Verbally describing the multiple dimensions of numerous inter-individual links in a systematic manner presents a procedural challenge for interviewees and interviewers alike. For this reason, in face-to-face interviews, interviewees were encouraged to keep track of the links already discussed by drawing a sketch map of their collaborations. The sketch map approach used is similar in some respects to that applied by Oancea et al. (2017). However, Oancea and colleagues propose iterating the sketch maps they produced with the help of interviewees, resulting in an agreed map (based on qualitative data). In DARE, the emphasis is on converting the narrative account into quantitative data, which in turn supports the generation of a map and indicators using software algorithms. In some cases the resulting map may be similar to that drawn by interviewees, however the DARE approach removes some of the subjectivity of the interviewee (and interviewer) in rendering the structure of the maps, which may be produced in a standardised way. Figure 2 shows two examples of sketch maps as drawn by interviewees for one of the cases (names are obscured to preserve participant anonymity). Sketch maps proved to be a practical way to structure the discussion. They served as reference points that facilitated looping back to prior parts of the narrative, recalling missed points and even on occasion aiding identification of major omissions (e.g. aiding recall of people previously not discussed).

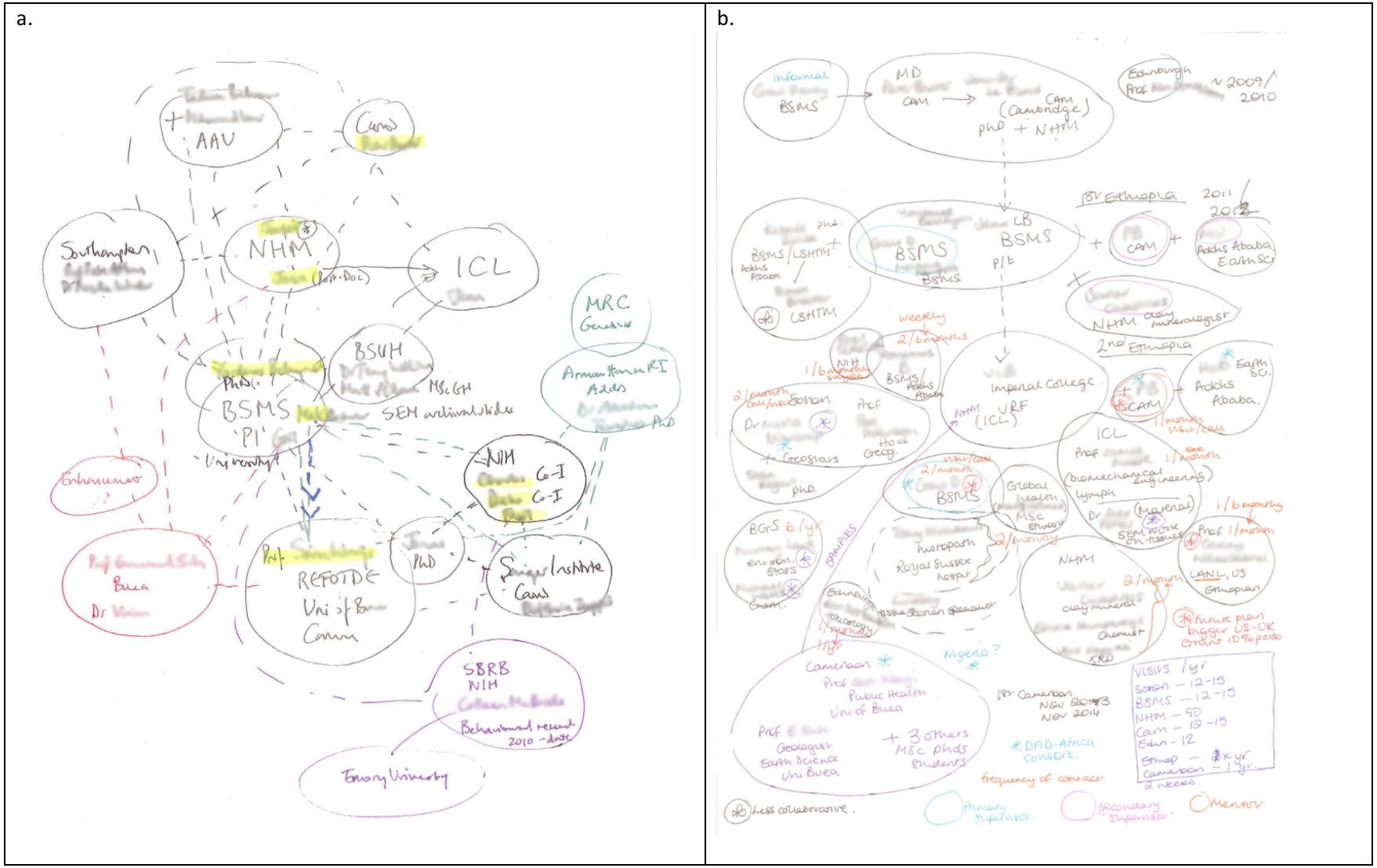

Figure 2: Drawings of project interactions produced by interviewees

Each sketch map features all participants in the research collaboration mentioned by the interviewee, and records the host organisation (represented by a bubble). The maps show which collaborators had ties pre-dating the start of the project - highlighted in yellow by one interviewee (Figure 2a), and starred by a second (Figure 2b). Some interviewees recorded additional information such as technical specialisations, work developed after the project finished (new project proposals, writing papers, …) and frequency of interactions. In other cases, this information was only provided orally. Organisational affiliation was also discussed and dual affiliations were noted and accommodated in the maps.

Telephone interviews provided a practical way to further document collaborative activity between dispersed teams. With the use of hand drawn maps precluded by this medium, telephone interviewees were asked to complete a matrix describing their relationships with other team members before the interview. This allowed telephone interviews to focus on their narrative account of the project and answer specific questions to address gaps left from other interviews.

Moving from qualitative to quantitative data

Interviews provided an opportunity for the interviewed team members to give a narrative account of the development of their research, the associated collaborations, its context, the challenges faced, the valued outcomes and further (anticipated) outcomes of the research. During this account, the interviewees were invited to discuss their ties with other team members within the collaboration according to each of the dimensions of diversity studied. The description of these ties allows them to be transformed into quantitative data. The conventions used for assigning quantitative values in this first application of DARE are summarised in Table 2, and further described in the DARE user guide (Bone et al. 2017) along with full interview protocols. As Table 2 indicates, different approaches are demonstrated so as to generate the maps and indicators for each dimension.

Interview data alone was used for the geographic, organisational, institutional and social dimensions. However, for the cognitive dimension, we used bibliographic data to describe the knowledge base of each individual participant and how it was influenced by the project, following previously established methods (Ràfols et al. 2010). This has the advantage of being able to estimate cognitive distances with reference to extensive bibliometric data providing a robust empirical basis for the analysis. Authors can be systematically positioned in cognitive space using the Web of Science subject categories (or other similar nodes within a global network of citations) as a proxy for their scientific experience and skills. Scientific fields that cite each other more rarely are characterised as cognitively more distant, and authors collaborating across these fields can be identified as engaging in comparatively rare bridging activities.

Assigning distances in the geographic dimension is empirically supported by observable spatial relations which can be measured in miles/ kilometres or in travel time. Previous research suggests that propensity to collaborate is negatively correlated with distance in a non-linear manner (Kraut et al. 1988) and so a non-linear scale may be appropriate for describing the efforts of bridging geographically dispersed teams. This reflects the finding that propensity to collaborate can drop off more quickly between labs in a building or buildings on a campus than between cities (ibid). For the purposes of our study, once an interviewee has identified a collaborator as being based in a given location, estimates of travel time between their locations were used (post-interview) to assign distance on a non-linear 6-point scale. Collaborating researchers in the same building have a distance of 0 on this scale, while those on different continents have a distance of 1 (with those on the same campus, same city, same region, or same continent occupying points between 0-1).

Distance in the institutional dimension is assigned using a scale distinguishing institutions through how they differ in the extent to which their missions share one or more of the following: commercialisation,

care, open science, education and policy (Llopis & D'Este 2016). The symmetric binary dissimilarity method (Han et al. 2012)is used to calculate institutional distance. Here, two individuals exposed to missions with the same series of objectives (for example two universities focused on open science and education) would be defined as having an institutional distance of 0, while those that differ completely could have an institutional distance of 1 (although the maximum seen here is between a commercial business and a university-hospital which have a distance of 0.8)[5]. This approach allows important distinctions to be made as individuals' institutional missions may not necessarily be the same as those of the organisation they work within, e.g. university researchers may be embedded in hospitals for logistical reasons (Lander & Atkinson-Grosjean 2011).

Distances can be described with higher or lower granularity where there is a well-defined prior empirical or conceptual basis. However where this is lacking, a simple scale is used to illustrate an operationalisation for the dimensions in question. For example, for the social and organisational dimensions, a three-point scale is employed to represent an interaction as present, partial or absent. Distances in each dimension are expressed as a value between 0 and 1. For example, we describe organisational distance as follows: individuals working within the same department are assigned an organisational distance of 0; those working in a different department at the same organisation have a distance of 0.5; those in different organisations have a distance of 1.

A simple 6-point scale was used to assign a value to interactions at interview, ranging from an intensity of 0 (where individuals did not interact) to 1 (where individuals interact at least daily), with annual, bi-annual, monthly, and weekly meetings occupying other evenly spread points in the scale. Again, without reference data to support the design of the scale, this distribution of points is to some degree arbitrary and could benefit from calibration in future development of DARE.[6]

Using this operationalisation of distances, maps are produced by first applying layout algorithms based on distances between individuals for each dimension. Once the layout has been set, the interactions between individuals are overlaid onto the graphs. The maps are produced using a force layout from the JavaScript library D3 (Bostock et al. 2011). This specific library simultaneously enables push and pull forces between the nodes represented in the maps. This feature is particularly helpful since each pair of individuals is assigned a distance. When the distance is small, the pull force overtakes the push force and *vice versa*, aiding clearer visualisation.

[5] See p.15 in the DARE User Guide (Bone et al. 2017).
[6] Further details of the methods used can be found in the DARE User Guide (Bone et al. 2017).

Table 2: description of variables used for proof of concept operationalisation of DARE

Dimension	Distance	Proxy used	Reference data	Prior literature
Cognitive	Distance in a continuous scale according to a WoS map of science	Cosine similarity using citations to journals associated to specific WoS categories	Distances between Web of Science Categories	Application is as used in Ràfols, Porter and Leydesdorff et al. (2010) on maps of science[7]
Geographic	Distance on a 6 point scale: Same building, same campus, same city, same region, same continent, diff. continent	Travel time between collaborating individual's places of work	Estimated travel time	None used
Institutional	5 point scale derived from the number of missions shared: Industrial, care, policy, education, and open science.	Degree of overlap of missions that collaborating organisations have in common calculated using the symmetric binary dissimilarity method (Han, Kamber, & Pei, 2012, pp. 70–71).	None	The institutional categories are provided by Llopis and D'Este (2016)
Social	3 point scale: List	Degree of acquaintance between two individuals	None	None used
Organisational	3 point scale: List	Membership of (one or more) organisational structures	None	None used

4. Analysis

This section illustrates how narratives, maps, and indicators can be combined in the operationalisation of DARE. Each case starts with some narrative on the project drawn from interviewees; next, the diversity of the team and changes in cohesiveness in the period studied are analysed with the aid of maps that provide a visual representation of the collaboration, together with quantitative indicators that provide a synthetic overview.

4.1 Case 1: Biomarker analysis platform

Project narrative

Grant funding for two years was awarded to support the development of a biomarker analysis platform with the aim of providing insights into the activity of candidate drugs for the treatment of

[7] The underlying metrics are publicly available in Leydesdorff's website: https://www.leydesdorff.net/overlaytoolkit/

cancer. The project ultimately involved 12 individuals, all working in the UK at the time. Industrial scientists were involved to oversee application of the new biomarker platform to cancer drug development programmes owned by a pharmaceutical firm. Two academic research centres from the same university-hospital were also involved. The academic research centre where the project PI was based hosted researchers developing the novel analytical platform. Researchers in the other centre provided access to the tumour samples on which the candidate drugs were tested.

The proposal was developed mainly by Mark and Oli with the help of Joe. Each were senior figures in their respective organisations.[8] Oli, who worked in a pharmaceutical firm, initially suggested to Mark that they collaborate on a funding application during a meeting at a conference. Within the window of time afforded by the conference, they outlined the proposal. Mark was particularly interested in using the award to promote the work of Chris, a junior researcher, who was developing the analytical platform that the project centred on. Chris took the lead in the implementation of the project. Mark and Joe played a supervisory role. Once the project had started Oli ultimately did not collaborate further with Mark or Chris, but did maintain regular research meetings with the other research group at their university.

In retrospect, the project was deemed a success by the researchers involved. They valued the relationships and experiences they had formed. Mark reported these links as the most valuable outcome of the project:

> "…putting different types of people and different skills together, I think that is so valuable and we need to do this more, we need to get out of our silos."

Mary, an industry collaborator, confirmed the quality of the collaborative engagement from the pharmaceutical firm's perspective:

> "…there was a lot of collaborative work and good scientific discussion which is not always the case and there was a lot of transparency in what was generated, good or bad, I think ultimately made it very successful and built a lot of trust on both sides"

Flo, a post-doc on the project, further confirmed the novelty of the extensive interactions:

> "The collaboration was the first time we [the two university-hospital research centres] worked together with a bigger group because before we always worked only with [Joe's] group… there would not be much of a collaboration before. But for this particular project there was a big interaction".

These benefits were particularly experienced by the junior researchers, who worked across the two academic centres for the first time. This is indicated by an increase in social and organisational cohesiveness indicators (discussed below). The project also enabled many of the university researchers to work with industry for the first time. While most of the senior researchers had previously worked with industry, this was not the case for most of the junior researchers. This was a valued opportunity as Flo reported:

> "It is always good to have the link with the pharmaceutical industry, because you can do different projects, you can do different things than just working on cell lines… …I wouldn't want to work just with cell lines for writing academic publications, I like more the clinical aspect as well, working with clinicians together with clinical trial samples and doing more assays which are more applied to patients as well."

[8] Individuals that were interviewed are assigned names – those that were not have been assigned numbers.

The analytical platform developed during Case 1 was adopted by other academic groups, aided by publications from the project. Subsequently the platform became the basis for a university spin-off company focused on providing services to pharmaceutical firms (not shown on the maps).

Project background: Team diversity

The indicators in Table 3 provide an estimate of the diversity of the project team for each of the five DARE dimensions. Diversity observed in Case 1 is generally lower than in the neglected disease epidemiology case (discussed below). The project involves only two distinct organisations (a firm and a university-hospital), and three institutional types (firm, university and hospital) out of a possible seven. The participants are all UK-based, albeit in two separate regions, and many of the researchers share their core discipline. The relatively small team size (twelve) also limits the potential upper boundary for the indicator of cohesiveness (further discussed below). Although the number of institutional types involved was limited, interviews revealed that the participation of individuals from different institutional types was crucial to the success of the project - in particular the inclusion of a clinician enabled access to the required bank of tumour cells.

The maps in Figure 3 give additional information about the diversity of the project team by displaying the distribution of nodes (individual researchers) across categories and space. The distance between nodes in the maps corresponds to their similarity with dissimilar nodes represented as more distant.

Features of the maps in Figure 3 are explained, dimension by dimension, to illustrate the value of studying these different perspectives of the same collaboration. In the organisational dimension the extent of links created between the firm and the university-hospital, and within the university-hospital are demonstrated (Panel A = before, Panel B = after), providing an indication of a valuable outcome for funders keen to foster university-industry links. The maps show that the outcome of the grant goes beyond reinforcing existing ties, with creation of many new ties that broaden the inter-organisational collaboration. In the institutional dimension (Panels C and D) individuals with duties spanning university and hospital institutional missions are included as separate categories so as to distinguish between those research active participants who primarily have medical duties from those that have primarily university responsibilities. The maps show that only one individual had clinical responsibilities - potentially a limitation. In this particular case, the geographic dimension (Panels E and F) shows structural similarities to the maps representing the organisational and institutional maps (Panels A to B, and C to D). However the social dimension (Panels G to H) makes clearly visible how each member of the project team knew at least two others before the project started, with the exception of two team members brought into the network as a direct result of the grant (post-docs Flo and Tim). In the cognitive maps (Panels I to J) the shaded circles are used to aid visualisation of some boundaries (but are not synonymous with the definition of categories in all cases). In this way, Panels I to J show that the project's researchers are all active in the field of oncology, but also that their expertise spans biochemistry, molecular biology, and haematology. These cognitive fields are relatively proximate when compared to more distant knowledge domains such as physics, or the social sciences. For example, one participant's subjective perspective may be that they benefited from working with "quite a multi-disciplinary group"; this can be contrasted with more objective data that reveals the extent to which the links in this collaboration cross disciplines, as compared to a wider set of scientific activities as a frame of reference for different cases. Indeed, this approach reveals that Case 2 is a much more cognitively diverse team.

Table 3: DARE indicators for Case 1, the Biomarker analysis platform

Analytical dimension	*Diversity*	*Cohesiveness before*	*Cohesiveness after*	*Mean distance bridged before*	*Mean distance bridged after*
Organisational	*0.42*	*3.10*	*12.99*	*0.17*	*0.27*
Institutional	*0.25*	*1.91*	*6.57*	*0.10*	*0.14*
Geographic	*0.24*	*1.78*	*7.21*	*0.10*	*0.15*
Social	*0.80*	*3.60*	*34.65*	*0.20*	*0.72*
Cognitive	*0.13*	*1.84*	*6.20*	*0.10*	*0.13*

	Organisational	*Institutional*	*Geographic*	*Social*	*Cognitive*
Before start of the project	*A* Academic centre - Mass spectrometry Academic centre – clinical biology Pharma company	*C* Researchers within university hospital Clinician in university hospital Industry	*E* Northern England Southern England	*G*	*I* Biochemistry Cell biology Haematology Oncology
After start of the project	*B* Academic centre - Mass spectrometry Academic centre – clinical biology Pharma company	*D* Researchers within university hospital Clinician in university hospital Industry	*F* Northern England Southern England	*H*	*J* Biochemistry Cell biology Haematology Oncology

Figure 3: Maps in five dimensions showing collaboration networks for Case 1 the biomarker analysis platform

Project activities: Team cohesiveness

Indicators in Table 3 show this project increased cohesiveness amongst team members in all the dimensions, supporting participants' statements to this effect. While the strongest rise is in the social dimension, this simply indicates that many new interpersonal connections were formed. Perhaps more relevant from a funder's perspective is a large increase in mean distance bridged in the organisational, institutional, and geographic dimensions; this indicates that a number of boundary-spanning connections have been established, particularly due to the broad collaboration between a university-hospital and pharmaceutical firm. Yet in the cognitive dimension there is only a small increase in collaboration across cognitive boundaries, but these may have been limited by a lack of opportunities to collaborate with cognitively distant collaborators (i.e. the diversity of the team was low in this respect).

The maps add further nuance to the interviewees' accounts, revealing that although cohesiveness increased due to many new linkages being formed, the strongest linkages (shown by thicker lines) continued to be within categories (i.e. within an organisation, institutional type, or region as shown in Panels B, D and F). Cohesiveness is revealed clearly by the intensity of links shown in the social dimension maps (Panels G to H) revealing more intensive collaborations between those working within and across the two academic research centres. These individuals mostly knew each other before the project began, but the new team members (Flo and Tim) joining the university-hospital both formed strong links across the two academic groups involved. This provides quantitative support for the statement made by an interviewed team member suggesting a "big interaction".

DARE's added value:

The association of awards with outputs and outcomes is a formal requirement of the funder in this case. Thus it is on public record that the team's grant led to a series of standard outputs and outcomes including publications, a patent application, a university spinout company, a method (the novel analytical platform formally licensed to the spin-out company), and follow-on funding awards. In this context, DARE provides information on the working relationships that supported these achievements with an accessible visual summary and helpful indicators of the extent of a collaboration with industry; this led to the development of a method deemed robust enough to form a spin-out firm, which in turn offered services of interest to several drug developers. The spinout, which involved Mark and Chris, was facilitated by Chris's experience with industry during this project. The mean-distance bridged indicator shows that during the project, the team worked across organisational, institutional and geographic boundaries and that, notably, the project relied on many new social connections. Yet the team was much less diverse in the cognitive dimension (the cognitive diversity indicator was 0.13 versus between 0.24 and 0.80 for the other dimensions). It is possible to speculate that this benefited the team by providing some common understanding and thus support for bridging activities. The study of further similar cases could elucidate the importance of having less distance in one or more dimensions to compensate for greater distance in others, with possible implications for programme design or project team selection.

4.2 Case 2: Neglected disease epidemiology

Project Narrative

Ann had been studying a neglected disease while working at a university in East Africa. She then led the development of a successful funding application for a 5-year project to facilitate her move to a UK university while allowing continued work on the epidemiology of the disease. Ann built her project team using established collaborators and new contacts in East and West Africa, the US, and the UK,

with the aim of studying both the environmental and genetics factors that caused the disease. To do so she planned to bring together expertise in geology, genetics and medicine. At interview, members of the team highlighted the importance of the cognitive links created through the project, emphasising these had made a key contribution to outcomes. Maria, a core post-doc on the project, expressed the uniqueness of the combination of disciplines brought together:

> "As far as I understand, this project is one of the only examples of where this is ongoing, earth scientists and medical communities coming together to address something like this."

Jane, another post-doc on the project, also reflected on this interdisciplinary and saw it as a strength:

> "…you need people from different backgrounds, you definitely need a geologist and need an epidemiologist but I think also including someone who understands epidemiology **and** spatial factors is also important." [Emphasis added]

Maria noted that there were challenges in working with other disciplines:

> "…clay mineralogy is even a huge different subject than volcanology, that I am used to, and working with geostatisticians has been incredibly eye opening. The approaches that you would use to address an issue are extremely different from an earth scientist to an epidemiologist, and so we are looking at very different resolutions."

Ann also described how she had to make sure she was able to work with both disciplines and develop a common language:

> "…we needed to talk the same language in terms of the type of strategy to be used. We used a lot of epidemiological terms, we had to make sure that that could be translated in terms that geologists could understand. And similarly, genetics has its own language as well, very technical. There is a bit of translation to do so that for example the geologists understand enough of that."

She also saw her role as a connector and facilitator between people working in the two different disciplines:

> "I suppose my role is different as I am not an expert in Geology and so I can bow to other expertise, but trying to help people from this background linking to people without any geology understanding in epidemiology and health teams."

As these quotes suggest, the project required expertise from different domains. Bridges between distant cognitive domains were created by several researchers other than the PI, Ann. Maria in particular created numerous connections which were important in accessing expertise from informal contributors, whose input played an important supporting role on the project.

Building connections between researchers across geographies was a key activity during this project, particularly between those working in the UK and Africa. Fieldwork trips to two geographically distant African countries were organised by Ann to collect data and soil samples, with the help of researchers from local universities. While formally based at Ann's medical school Eva, a PhD student, spent a large amount of time in Africa to complete the fieldwork. These trips enabled the team to build working collaborations for the project. These are visible on the maps, particularly through the geographic dimension (see below).

The project led to an extensive series of outcomes, including significant developments in understanding of the neglected disease leading to better treatments in the region studied.

Project background: Team diversity

The team for Case 2 is substantially larger than in Case 1, with a total of 35 researchers taking part. A notable feature of the project is that only 17 of those involved in the research were formally associated with the project (i.e. named in the bid, or formally hired to work on the project). Other participants had informal, but nonetheless important, roles. An example of an informal role during the project is the training of early career researchers in techniques required by the project. Such was the scale of the network developed that core participants were not always aware of the contributions played by peripheral participants. This demonstrates the importance of conducting interviews with multiple participants to reveal the full network that have supported eventual outcomes. The maps in Figure 4 distinguish between formal and informal participants with nodes of different sizes. Larger nodes denote participants formally involved in the project, while those represented by smaller nodes played informal roles.

The maps in Figure 4 display the distribution of individuals across categories in each of the five dimensions while Table 4 shows the indicator values for each of the five dimensions of diversity. Notably, the diversity score is higher in each dimension for Case 2 when compared to Case 1. The dimensions with highest diversity indicator scores are the organisational and geographic, reflecting the distribution of the team across many different organisations and the spread of these across the globe. The organisational dimension maps (Panels A and B) show that thirteen different organisations were involved in the project, and that there was quite an even distribution of individuals across these. This generates the high value for the organisational diversity indicator in Table 4. The geographical dimension maps (Panels E and F) show a high concentration of individuals in the UK but the inclusion of participants in different continents (the US and Africa) leads to a high indicator score for geographic diversity. The cognitive maps (Panels I and J) highlight the project brought together individuals from both biomedical and earth sciences, with a variety of disciplines in each of these broad fields involved. The cognitive diversity indicator in Table 4 shows that the team is highly diverse (much more than in Case 1), supporting the reported experiences of the interviewed team members.

The institutional map shows that although several types are included, there is a high concentration in the university category or categories where individuals have duties that follow a university institutional mission. Individuals with duties spanning university and hospital institutional missions are included as separate categories in Panels C and D. This allows us to distinguish between researchers primarily involved in research and those primarily involved in care, even when both are based in a hospital. This is important to represent because medics with greater time spent on care-related duties rather than research or teaching may find it harder to engage in research activities. The institutional diversity indicator in Table 4 is not as high as for the other dimensions (although it is slightly higher than for Case 1) because most of the participants worked at universities. Social diversity is also relatively high, reflecting a large team of collaborators who largely did not know each other before the project. This is visible in Panel G, which shows many unconnected individuals at the start of the project.

Table 4: DARE indicators for Case 2, the neglected disease epidemiology

Analytical dimension	*Diversity*	*Cohesiveness before*	*Cohesiveness after*	*Mean distance bridged before*	*Mean distance bridged after*
Organisational	0.9	15.4	96.4	0.41	0.64
Institutional	0.28	5.72	25.08	0.15	0.23
Geographic	0.74	11.92	57.12	0.32	0.53
Social	0.92	0.32	68.8	0.01	0.64
Cognitive	0.56	12.6	44	0.34	0.41

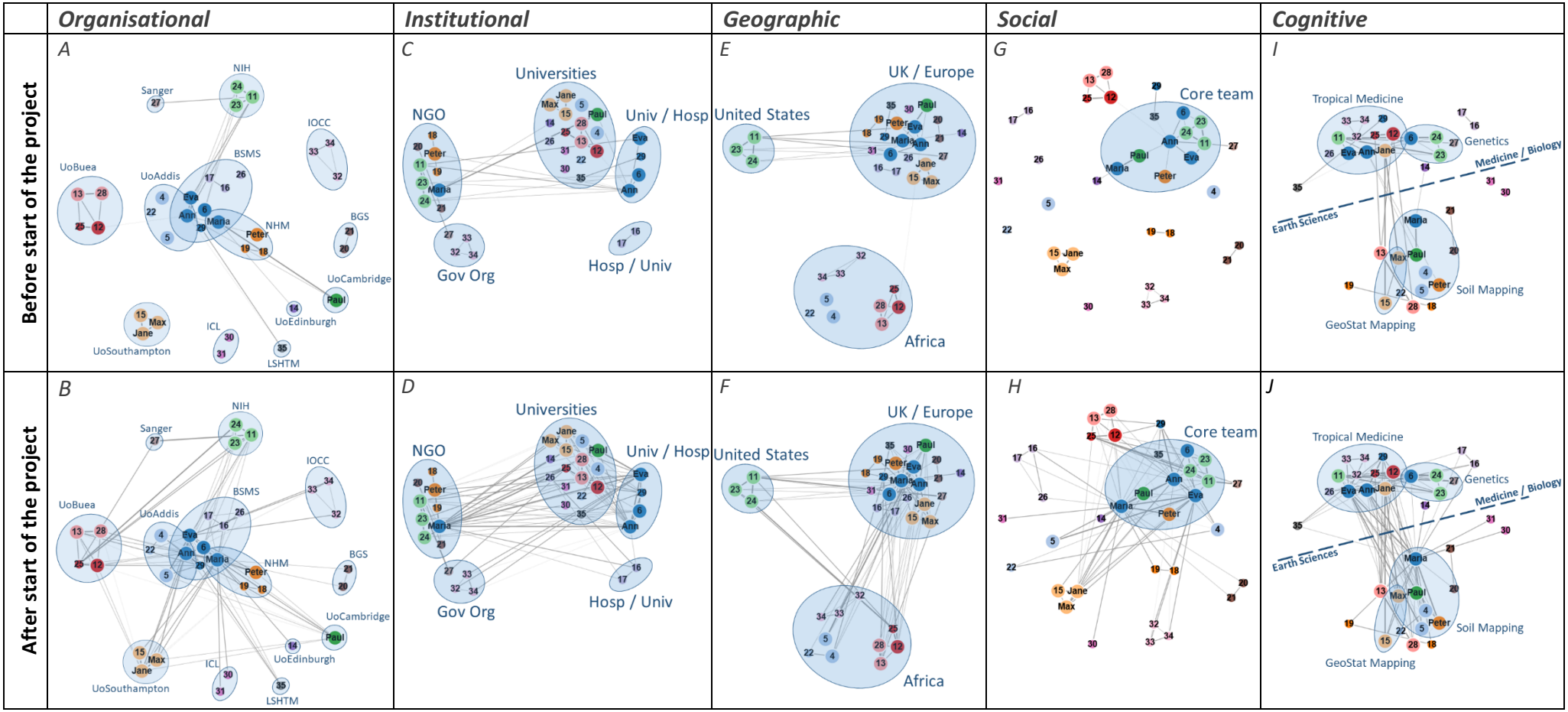

Figure 4: Maps in five dimensions showing collaboration networks for Case ,: the neglected disease epidemiology

Project activities: Team cohesiveness

Table 4 shows that the neglected disease epidemiology project led to large increases in the cohesiveness indicators in all dimensions. Increased cohesiveness is associated with the establishment of new links as well as intensification of existing links. In this case, the maps reveal that it is the creation of many new links that mainly contribute to increased cohesiveness. This is most visible in the social dimension maps (Panels G and H) which show the extent to which PI Ann and post-doc Maria increased their personal networks as a result of this grant. Cohesiveness is also higher for this case compared to Case 1, partly due to the higher number of individuals, but also the underlying diversity of this collaboration is higher.

In Figure 4, Panels A and B show that many inter-organisational links were formed. In particular, individuals such as Ann and Maria held positions in two organisations concurrently, which was explained at interview to be important for the progress of their work. In the institutional dimension it is clear that many links also span boundaries (e.g. universities and university-hospitals working together) as well as with organisations that have a policy-focused mission such as NGOs and governmental organisations. In the geographic dimension, a large increase in the cohesiveness indicator reported in Table 4 is due to inter-continental collaboration between African and UK researchers as well as, to a lesser extent, researchers in the US (as shown in Figure 4, Panels E to F).

The mean distance bridged indicator in Table 4 provides a simple summary of the extent to which boundaries were crossed in the different dimensions during the collaboration. These capture the substantial geographic bridging that the project achieved. Similarly, the mean distance for organisational and institutional dimensions increased suggesting the project facilitated the development of links across organisations and institutions more than it has encouraged collaboration within them. The extensive interdisciplinary work between biomedical and earth sciences is reflected in the rise in mean distance bridged in the cognitive dimension, while the mean distance bridged in the social dimension shows the strongest rise, emphasising just how frequently individuals formed links beyond their prior networks as a result of the project.

DARE's Added value:

Classic research evaluation, as required by the funder of this project, requires reporting of outputs and outcomes and reveals the extensive publications, follow-on funding, and details of the impact of this project. The project informed scientific understanding of the diseases' causes, and provided a significant stream of new publications in a relatively sparse prior literature. Awareness of the disease was raised among local communities and internationally with resulting policy changes. A treatment regime and prevention strategy were developed, and these have subsequently benefitted tens of thousands of people. The DARE analysis shows how the project was catalytic, by building a strong network that supported a series of further funded studies. In particular the PI's success in engaging so many informal collaborators in Africa, the US and UK was an early sign of later progress, and one that would not be as clearly identified even by looking at publication outputs. DARE also provides a basis for supporting the team's claims about the extent to which the project created capacity enhancing North-South research links (much valued by the project's funder) as well as objectively recording the extent to which the project was interdisciplinary.

3. Discussion and Conclusions

By building on prior concepts and frameworks by Boschma (2005), Ràfols (2014), and Molas-Gallart et al. (2016), DARE provides an original method combining narrative, maps, and indicators, to support a multi-dimensional analysis of teams engaged in knowledge production and application. DARE emphasises the importance of team diversity and the changing nature of links between individuals during collaboration. As such, it can inform the fundamental understanding of the role and contribution of diversity and cohesiveness in research collaborations. The method allows the extent of bridging efforts between diverse individuals to be determined and the relationship between these and subsequent outcomes to be studied.

The analysis in this article shows how two particular research grants each led to the formation of new team-based research collaborations that delivered valued outcomes. It shows the extent to which the two projects brought together diverse individuals, many of whom shared no prior connections, and the extent to which they combined expertise from different disciplines and organisations spanning different types of institutions and geographies. While such statements may often be made by teams, DARE provides a means to record claims about the diversity of the team and the efforts they made to work together. The two cases were selected because of their expected differences, and these are revealed by the analysis. Case 1 (the smaller team, working on a shorter project based solely in the UK) clearly has lower indicator scores than Case 2 (a larger team, funded for more than twice as long in duration, working across three continents). More unexpectedly, the approach revealed the extent to which one team had recruited informal contributors during their project, as well as the large differences in cognitive diversity between the two projects. Also displayed are strong links that have been important for further work by both teams in very different ways. In Case 1, industry links provided vital experience that helped the core team members to start their own spin-off company. In Case 2, the formation of an international network supported further research projects and ultimately led to improvements in the treatment of many thousands of people.

It is possible to see how these insights may be helpful to funders to verify claims made by teams, or for teams to demonstrate early signs of progress in their research collaborations even before outputs emerge. However, with a wider dataset of cases it may in time also be possible to relate starting conditions (such as team diversity in particular dimensions) or processes (such as ways of enhancing cohesiveness) with outcomes and other causal relationships.

DARE can also provide a versatile new method for research evaluation. Research evaluation approaches can be described as configurative or aggregative; the former focuses on the processes used and values held by researchers and wider stakeholders, while the latter seeks to quantify impact or value created by initiatives (Oancea et al. 2017). DARE has elements of both these approaches as it aggregates data on interactions and also describes the characteristics of teams and the processes they follow in their collaboration. Another important distinction is between prospective and retrospective research evaluation modes (Oancea et al. 2017). While DARE is demonstrated in this article as a way to track changes retrospectively (while still potentially being able to detect informative changes earlier than post-hoc methods reliant on outputs), elements of DARE could be used prospectively for multi-dimensional characterisation of research teams and their base-line cohesiveness.

Arguably, the versatility of our approach makes it broadly applicable, and with this objective in mind the following observations are made with a review to refining the approach for further use.

First, the five dimensions discussed here are not necessarily the only ones of interest in research evaluation. For example, others such as gender, culture, or career stage could potentially be operationalised using the formulae developed and demonstrated here. The use of further dimensions may provide a more detailed understanding of the roles of these diversities in research collaborations, the challenges they pose and the ways in which these may interact, perhaps with low diversity in some dimensions compensating for challenges raised by high diversity in others (Boschma 2005).

Second, the method is flexible in terms of the timing of data collection and analysis. Data could be collected throughout the life of a collaboration or after it has finished. Indeed the 'start' and 'finish' comparisons (used in Case 1 and 2) may be of particular interest when evaluating specific interventions. Static or dynamic analysis of the structure of a particular research collaboration or broader network could be undertaken. This could be helpful for understanding causality in attributing outcomes to inputs, and importantly, for understanding the benefits of particular ways of working together. DARE has the ability to track various interventions in this way.

Third, it may be possible for DARE to be used with different types of data from those used here. For example, data routinely collected by funders or research host organisations could be re-used for DARE, reducing the burden of new data collection in the application of DARE.

This initial application of DARE has highlighted some avenues for future exploration and some limitations to be addressed through further development. Future application could extend beyond the biomedical domain as there are no apparent conceptual reasons preventing this. Application beyond the short, team-based projects (Case 1 and 2 were projects lasting 2 years and 5 years respectively) is also theoretically possible. However, cases of longer duration or size require adequate resources for suitable analysis - or the DARE method requires adaptation to facilitate scaled up data gathering. Some technical and practical limitations are discussed below, as a first step towards further development of DARE.

Access to data: In this study we used face-to-face and telephone interviews as the primary means of data gathering. For this to be possible, the analyst requires good access to the core research team and their wider collaborators, some of whom may be very peripherally involved in the focal case. Projects with many peripheral actors may be difficult to map if these individuals are difficult to engage. Yet, the more individuals that are engaged during data gathering, the more the indicators and maps will reflect the achievements of the research collaborations studied.

Robustness: When the studied researchers are active in one or more ongoing lines of research, it can be difficult to distinguish the individuals and activities that took place within the bounds of a particular project or initiative. This is particularly a problem when individuals are working on several projects simultaneously, or in a series of projects over an extended period of time, or where they are not formally part of the focal team. An iterative approach to data collection may be required, for example by clarifying details with the PI or core team members to determine the inclusion or exclusion of particular activities as comprising part of the initiative being studied. Norms for the inclusion or exclusion at the boundaries of teams need to be developed in the analysis, particularly where comparative analysis of multiple teams is required.

Resources: In its present form, DARE is resource-intensive for the analyst as face-to-face interviews can take 90 minutes or more, particularly for core team members (although subsequently, 45 minute telephone interviews with additional team members have been useful for gap filling and verification). Refinement of the interview instruments or development of a survey format, coupled with development of software interfaces to capture and analyse input data in a streamlined manner, could enhance efficiency by reducing the time burden of those being studied.

Availability of a frame of reference for dimensional scales: for some dimensions (such as the organisational and the social) the indicators used here are very coarse due to the lack of clear frames of reference. Further empirical evidence could help refine the indicators in these dimensions. Only in the cognitive dimension is it possible to judge whether the interactions in a given case are rare or common, with respect to a well-characterised broader population of collaborations described by the body of published research. Even here, a limitation exists, in that team members with no publications (e.g. research assistants, students and early career researchers, or non-academic stakeholders) are difficult to place onto maps alongside those who have publication profiles. Interview methods could be used to generate a cognitive profile for those that have no publications (e.g. allowing interviewees to identify subject categories that best describe their training) and might be matched against data on the prevalence of skills more generally. Likewise, reference data on the frequency of research collaborations across geographic distances for a large body of scientists could be used to calibrate scales used in that dimension. Until these frames of reference are assembled, application of the indicators may rely on qualitative estimates and comparisons across dimensions, for example in understanding the implications for trading off distance in one dimension with distance in another, as undertaken by Lander (2015).

Cross-case comparisons: The availability of indicators invites quantitative comparisons between different cases; yet, without known outcomes from a wide range of comparator cases, it is not possible to make strong claims about the impact of diversity and cohesiveness on performance. Care also needs to be taken to compare like with like, for example in terms of team size and project duration if normative judgements are to be made on performance. Longer projects clearly provide more scope for cohesiveness and larger teams provide more scope for diversity and cohesiveness. With limited reference cases, DARE is best used for formative, rather than summative, evaluation.

There is substantial interest in the role of distance (proximity) in innovation processes and much to be explored (Davids & Frenken 2014). Therefore, despite the limitations of the DARE method as presented in its prototypical form in this article, there may be substantial utility in applying the concepts of diversity and cohesiveness to the study of research collaborations. Central to this approach is a multi-dimensional view of collaborative processes that values the contribution of diversity and acknowledges the challenges it brings, as well as the importance of understanding its role in knowledge creation and, ultimately, societal impact. It is anticipated that this approach will be useful in addressing a wide range of questions for the study of team science and other forms of collaborative interactions more broadly, in academic, industrial, and policy contexts.

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Annex

I. Questionnaire for interview

Section 1: Background

Researcher personal background

1.1) Please give a brief description :
   a) of your career path
   b) of your current role in your organisation

General information about the case study project

1.2) Please describe the case study project in a few words, with its objectives:
   a) What is the involvement of your organisation from inception to the end of the project?
      i) And your specific role (*individual to the researcher*)

Mapping exercise:

1.3) Please list the people involved from your organisation (including people working part time).

1.4) Indicate where people work, on the same site/campus, on another site/campus, in the same building or another building?
   a) What type of organisations do the projects members work in (and organisation type, e.g. university, charity, Firm, Hospital….)?
   b) Are the people you **report** (line of management for the project) to different from the ones you were reporting before you started the project?
      i) If so, please explain why?
      ii) (NOT PI) Who are you reporting to? Are they within your organisation?
      (1) If you report to people from other organisations, has reporting to people elsewhere changed expectations about the nature of your work and its potential results?
   c) How are you **organised within your site team** (who do you exchange with -informal arrangements-?) In practice who did you work with most during the project?
   d) Could you describe how the work was organised with the other members of the project team? (Frequency of meetings and interactions)

      i) What was the frequency of interactions before the project started?
      ii) What are their roles within the project?
      iii) Did you or people in your organisation already know them or work with them before the project? **
      iv) How often do you meet with the people in the other organisations and what is the purpose of these meetings?

1.5) How much time (days per year) have you spent with each person as a result of the project? Is it different from the time spent together before?

1.6) During the project did any of these individuals visit your site (or you visited their site)? How did it differ from the visit before the project started? *(only for partner organisations)*

If yes,

a) What were the purpose and duration time of these visits

1.7) Does sharing the same site as your project colleagues affect the way you work? How? *(only for partner organisations)*

1.8) Do they have a **different background**, specialisation or experience than you?

If yes,

a) What are these backgrounds or bodies of experience?
b) Was it the first time you worked with these specific individuals? **
c) Was it the first time you worked with scientists/technicians with these types of background/ experience?
d) Has this collaboration affected your knowledge and awareness of complementary knowledge capacities necessary for the completion of the project or useful in future? And if so how?

1.9) Can you indicate which organisations you have not worked with before? Can you indicate whether they are entirely new types of institutions?

1.10) Were there any difficulties in your collaboration relating to the way you are working? What are they? Do you have different goals? (when publishing)

1.11) **After the project finished** did you still meet or keep in contact with those colleagues (work or non-work related interactions)?

If yes,

a) How often?
b) By which means and how did these interactions change compared to before the project started?

1.12) Have relationships with colleagues/ stakeholders you knew before the project changed as a result of the project and how?

1.13) Do you think collaborating in this project has changed the relationship of trust with colleagues/ stakeholders in the project?

If yes,

a) Could you describe this change?

Section 2: Your organisation

2.1) What are the main (formal and informal) criteria used within your organisation to assess your performance? (we are interested in perception here, Human resources and direct supervisors?)

2.2) Does the performance criteria from the funder differ from your organisation? If yes how?

2.3) Did the project seek to address goals which are different than the performance criteria (or part of) of your organisation?

2.4) Has the work on this project involved you becoming engaged in work you don't normally undertake? If yes, are they valued by your organisation?

2.5) Do individuals face different institutional pressures or incentives between organisations involved in the project?

Section 3: Outcomes

3.1) What are the main outcomes (broadly defined) that came out of the project of real value?

a) How has this project changed your work or your vision of the future?
b) How has it changed work of others?
c) Are there outputs (including methods, policy implications not just publications) that are under development, and if so what are these?

3.2) Would you do it again (from 0 to 5 likert scale)? Why (that scoring)? (ask about difficulties vs outcomes)

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