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# Interdisciplinary researchers attain better long-term funding performance

Ye Sun[1,8], Giacomo Livan [2,3✉], Athen Ma [4] & Vito Latora [1,5,6,7]

Interdisciplinary research is on the rise globally. Yet, several studies have shown that it often achieves lower impact compared to more specialized work, and is less likely to attract funding. Here, we seek to reconcile such evidence by analyzing 44,419 research grants awarded by the research councils in the UK. We find that researchers with an interdisciplinary funding track record dominate the network of academic collaborations, both in terms of centrality and knowledge brokerage, but such a competitive advantage does not translate into immediate return. Our results based on a matched pair analysis show that interdisciplinary researchers achieve lower impact with their publications in the short run; however, they eventually outperform their specialized counterparts in funding performance, both in terms of volume and value. These findings suggest that pursuing an interdisciplinary career may require perseverance to overcome extra challenges, but can pave the way for a more successful endeavor.

[1] School of Mathematical Sciences, Queen Mary University of London, London E1 4NS, UK. [2] Department of Computer Science, University College London, London WC1E 6EA, UK. [3] Systemic Risk Centre, London School of Economics and Political Sciences, Houghton Street, London WC2A 2AE, UK. [4] School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, UK. [5] Dipartimento di Fisica ed Astronomia, Università di Catania and INFN, 95123 Catania, Italy. [6] The Alan Turing Institute, The British Library, London NW1 2DB, UK. [7] Complexity Science Hub Vienna (CSHV), Vienna, Austria. [8] Present address: Department of Computer Science, University College London, London WC1E 6EA, UK. ✉email: g.livan@ucl.ac.uk

nterdisciplinary research is increasingly regarded as the key to tackle contemporary complex societal challenges and to stimulate scientific innovation[1–3]. As high-impact discoveries often occur at the intersection of disciplines[4,5], scientists have become more engaged in research areas that transcend the boundaries between traditional fields[6,7], and increasingly collaborate across such boundaries[8].

A higher uptake in interdisciplinary research has been widely reported across academia[9], as there is now a much greater level of knowledge transfer between subjects among researchers[10]. Yet, these trends are somewhat intriguing when one looks at the evidences available on research outcomes, which suggest that—more often than not—interdisciplinary research may be an unrewarding enterprise in today's highly competitive academic environment. In fact, it is only interdisciplinary work based on proximal combinations of different fields that achieves recognition and impact (as quantified by accrued citations), whereas distal combinations are usually perceived as too risky or heterodox[11]. Similarly, interdisciplinary research is often associated with lower citation rates[12]. For example, Levitt and Thelwall[13] analyzed the publications from two selected years in the Scopus dataset and found that in the fields of life sciences, health sciences, and physical sciences, the average number of citations received by monodisciplinary articles is approximately twice that of multidisciplinary articles. Furthermore, by examining the research proposals submitted to the Australian Research Council's Discovery Programme over 5 continuous years, Bromhaml et al.[14] determined that interdisciplinary projects are less likely to be funded than those with a specialized focus.

Here, we ask whether interdisciplinary researchers share the same gloomy outlook in a longer time span and wider database. To this end, we compare the career progressions of researchers with a track record of research funding that can be unambiguously classified as either interdisciplinary or monodisciplinary. We examine data detailing more than 44,000 research grants funded between 2006 and 2018 by the seven discipline-based UK national research councils (collectively forming the bulk of the largest public funding body in the UK), which provide funding to universities and academic institutions to undertake research across a broad spectrum of fields, including arts and humanities, biology, economics, engineering and physics, medicine, environmental sciences and astronomy (details in Methods and Supplementary Table 1).

Through network analysis, we discover that researchers active across different disciplines play a crucial role of knowledge brokers in the academic collaboration network, bridging the gap between subjects and researchers that may otherwise remain disconnected. By means of a matched pair experimental design we find that, despite achieving comparatively lower impact, in the long run interdisciplinary researchers outperform their discipline-specific peers in funding performance, both in terms of number of grants and their funding size. Our findings help explain the continuous drive on interdisciplinary research, and provide insights on its role in the modern research funding landscape that may be useful to researchers and funding bodies alike.

## Results

**Evolution of cross-council behaviors**. Between 2006 and 2018, the average team size increases over time, with team composition becoming more cross-institutional (Fig. 1a, b). This demonstrates an increasing trend of collaborative science in the UK funding landscape, which is consistent with rising teamwork and multi-institutional research in scientific publications[15–17]. A funded project can be associated with one or more research subjects out of 104 possible subjects. The level of cross-disciplinarity shows an upward trajectory (Fig. 1c), with nearly half of funded projects (44%) being related to at least two research subjects.

The above finding is consistent with the general shift towards more cross-disciplinary research[1]. However, it does not specify whether the same consideration may apply to individual researchers. To examine this, we divide the investigators into two groups: cross-council investigators and within-council investigators. The former are those who have obtained funding from at least two different research councils; while the latter are those who have received funding from one research council only. Admittedly, this is a rather coarse-grained separation that does not account for the different sizes of different councils and potential overlaps between them. Yet, let us reiterate that the fundamental units of our analysis are researchers. In this respect, we expect such separation to be able to capture fundamental differences in terms of career choices and breadth of research interests. In particular, we expect the cross-council investigators cohort to be made both of genuinely interdisciplinary researchers (i.e., those active in areas at the interface between well-defined disciplines) and multidisciplinary researchers (i.e., those active in more than one well-defined research area). Although such difference may be relevant in other contexts, in the following we will take the position that being a cross-council investigator represents the main indicator that a researcher seeks funding to push disciplinary boundaries with their work. To examine how the two groups of investigators evolve over time, we calculate the fraction of cross-council investigators in each year, and observe a marked increase as expected, from around 0.17 in 2006 to 0.26 in 2018 (Fig. 1d).

To better understand how this rise in cross-council investigators alters the funding landscape, we construct a co-activity network whereby nodes represent research councils. Two councils share a link if they both have supported at least one investigator, and links are weighted with the ratio between the observed number of investigators funded in both councils and the expected number based on a randomized null model (Supplementary Note 2). Starting with the 2006–2008 window (Fig. 1e), cross-council investigators are most commonly found between BBSRC and MRC, and between BBSRC and NERC. A decade later (2016-2018 window), the co-activity network becomes fully connected (Fig. 1f) with two new links connecting AHRC with MRC and STFC, respectively. In addition, the link weights of cross-council investigators between BBSRC and NERC, and between AHRC and ESRC soar by 29% and 90%, respectively. These shifts in the funding landscape appear to be the response to the UKRI policy to support research across council boundaries and enhance the culture of multidisciplinary research[18].

Elite institutions have been found to be prime recipients of research funding, as they are key in orchestrating collaborations[19] and generating research outputs[20,21]. We consider the total amount of funding received by institutions between 2006 and 2018 as a proxy of their national rank, and examine the level of cross-council activities among their investigators. For the sake of simplicity, institutions are grouped into two tiers, with the top tier consisting of 40 institutions (Tier I) that have received a higher than average total funding over the aforementioned 13 years period, and the remaining institutions forming the bottom tier (Tier II). There are noticeably more cross-council investigators in top tier institutions (Fig. 1g, h and Supplementary Note 3), in line with previous findings on the governing role on research innovation among top institutions[22]. On the other hand, the proportion of cross-council investigators in the bottom tier shows a bigger increase, from 18% to 26%, which is twice that of the top tier (with an increase from 27% to 31%).

**Structural advantage in the collaboration network**. Our results have shown that interdisciplinary research is undoubtedly gaining
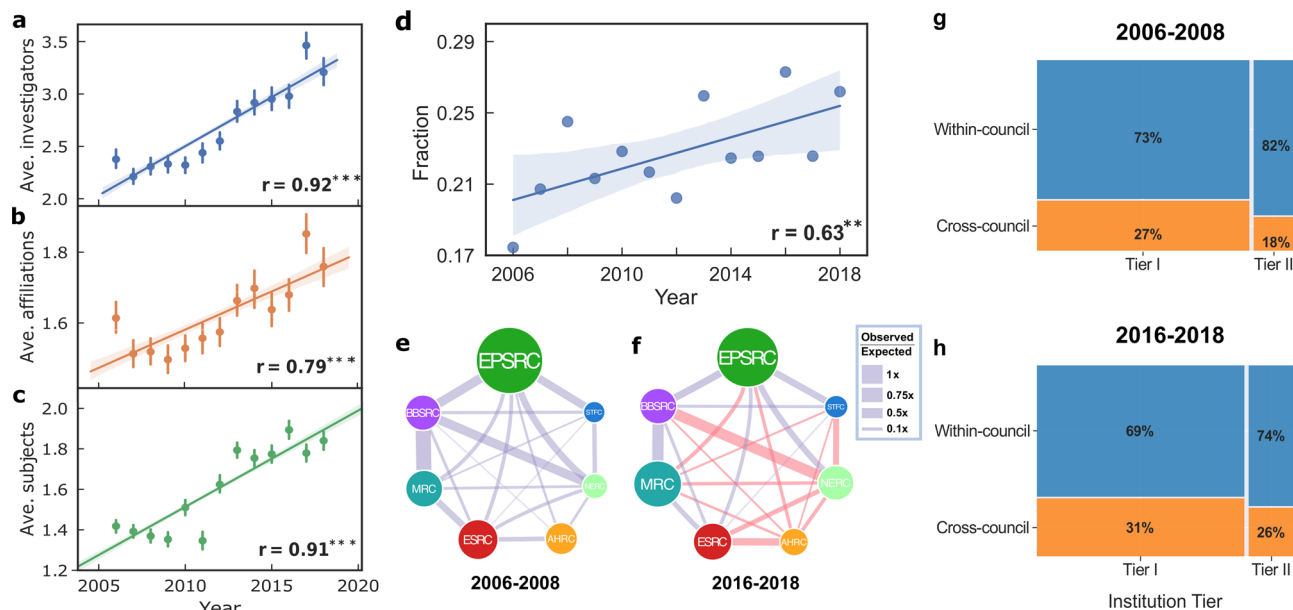
**Fig. 1 Time evolution of the funding landscape. a** The typical number of team members per grant shows a significant increase over time. **b** The average number of affiliations participating in each grant grows with time. **c** The average number of subjects listed in each grant continues to rise over time. In panels **a** to **c**, the error bars indicate 95% confidence intervals. **d** The fraction of cross-council investigators increases over time. In panels **a** to **d**, the solid line and the shaded area represent the regression line and 95% confidence intervals, respectively. Each regression has also been annotated with the corresponding Pearson's r. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. **e**, **f** The co-activity network of investigators in two time windows, 2006–2008 and 2016–2018. Node sizes are proportional to the number of investigators that have received funding from each research council. Two councils are connected if they have both supported at least one investigator, and the link width is weighted by the ratio between the observed number of investigators funded in both councils and the expected number based on a randomized null model. Here, seven research councils are considered: Arts and Humanities Research Council (AHRC), Biotechnology and Biological Sciences Research Council (BBSRC), Economic and Social Research Council (ESRC), Engineering and Physical Sciences Research Council (EPSRC), Medical Research Council (MRC), Natural Environment Research Council (NERC) and Science and Technology Facilities Council (SFTC). Compared to 2006–2008, the links with increased weights in 2016–2018 have been highlighted in red. **g**, **h** The percentage of cross-council investigators in different institutional tiers and periods. Here, the research institutions are stratified into two tiers by checking whether their total awarded funding is larger than the average amount per institution (i.e., $1.02 \times 10^8$). Box widths are proportional to the number of investigators in Tier I and Tier II, respectively. Box heights are proportional to the percentage of cross-council and within-council investigators. The institutions in Tier I have a higher proportion of cross-council investigators than those in Tier II in both 3-y time windows ($\chi^2$ test $p < 0.0001$, odds ratio = 1.67 for 2006–2008; $p < 0.0001$, odds ratio = 1.28 for 2016–2018). The same conclusions have been reached when different time window lengths and different criteria of institutional stratification have been used (see Supplementary Note 4).

momentum, with more cross-council investigators emerging across the university sector. To better understand this shift in collaborative science, we examine research partnerships among investigators and study the roles played by the cross-council and within-council groups. Here, network nodes are the investigators, and two investigators are connected if they have partnered in one or more research projects.

Cross-council investigators consistently show a much broader collaborative practice with a much higher average degree (Fig. 2a). They are also more likely to occupy prime locations or gateways for information dissemination, as demonstrated by both a higher closeness and betweenness centrality. Indeed, we find that cross-council investigators are much more likely to be brokers of information—as they are characterized by a higher average effective network size[23]—suggesting that they play a central role in establishing partnerships. Overall, the more diversified their funding source, the more advantageous their network position appears to be (Fig. 2b). By comparing the two groups of investigators with respect to their number of grants, our results on network metrics show systematic differences in their collaboration patterns (Fig. 2c), and the differences are most apparent among the more successful investigators.

**Research outcomes and scientific impact**. Is there a detectable difference between the cross-council and within-council

investigators in terms of research outcomes and scientific impact? To address this question, we need to control for the bias caused by possible confounding factors, so that the observed differences in research outcomes and scientific impact between the two groups can be more confidently ascribed to interdisciplinarity (i.e., cross-council funding behavior). Here, we perform a propensity score matching analysis[24] whereby the career profile of a principal investigator (PI) is characterized by five confounding factors, namely the institutional ranking (measured by the total amount of funding received by the PI's institution), the number of grants awarded to a given PI, and their average funding value per grant, team size and project duration. The last three factors have been adjusted to account for variations in values in different disciplines, and over time (Supplementary Note 6 and Supplementary Fig. 10). A cross-council investigator is then paired with a within-council investigator if the two share a comparable career profile between 2006 and 2013 (Fig. 3a), thereby eliminating the effect of these confounding factors on the phenomena under investigation (Fig. 3b and Supplementary Fig. 11). The analysis yields a total of 958 pairs of cross-council and within-council PIs.

For each matched pair of PIs, we compare their research performance based on the achievements reported in their grants awarded during 2006 and 2013 (but omitted projects that go beyond 2018 as the achievements reported would be incomplete), including the average number of papers reported per project, the average number of total citations received per grant, and the
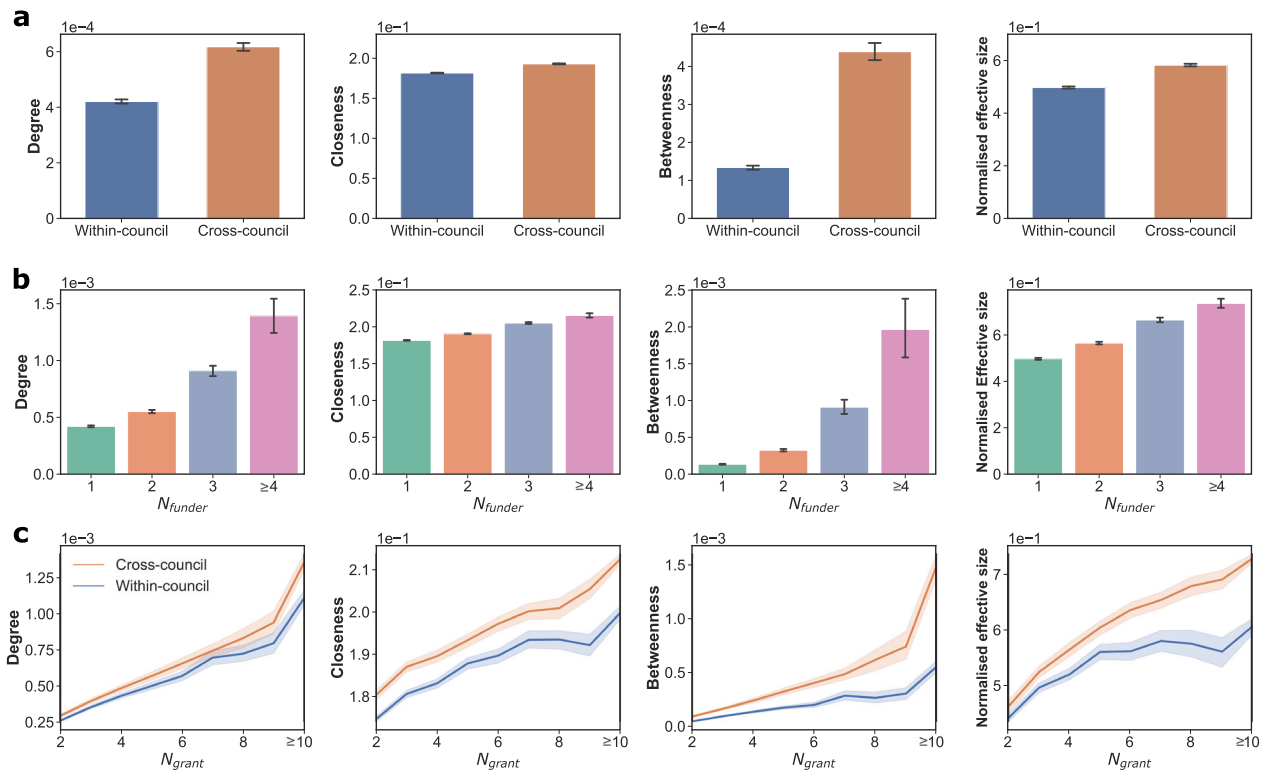
**Fig. 2 Structural advantage of cross-council investigators in the collaboration network.** Each column corresponds to a different network property, namely: degree centrality, closeness centrality, betweenness centrality and normalized effective size. **a** Cross-council investigators significantly outperform the within-council investigators in all four network properties (Welch's $t$-test, $p < 0.001$ in all cases). **b** Network metrics among investigators increase with the number of councils ($N_{funder}$) they have received funding from. **c** Cross-council investigators consistently have a network advantage over within-council investigators with reference to degree, closeness, betweenness and normalized effective size. $N_{grant}$ denotes the number of grants received by investigators in cross-council and within-council groups. The error bars and shaded areas represent 95% confidence intervals.

average number of citations received per paper per grant. Again, these metrics have been normalized across the different disciplines, and over time (Supplementary Note 6). We observe that while the two groups of investigators produce more or less the same number of publications, cross-council investigators clearly receive less citations in general than their within-council counterparts (Fig. 3c and Supplementary Table 2), both in terms of total citations ($t$-test, $p=0.0021$) and mean citations ($t$-test, $p=0.0004$), which is consistent with findings in prior studies[6,12].

**Long-term funding trajectory**. We finally compare the funding trajectory of cross-council investigators to that of within-council investigators. We refer to 2006–2010 as the in-sample period where investigators are paired, and 2011–2018 as the out-of-sample period in which funding performance of each pair of investigators is compared (Fig. 4a). On this occasion, the pairing is done by not only matching their career profiles but also their research performance (i.e., reported achievements in grants described in the previous section, Fig. 4b and Supplementary Fig. 12), yielding 709 investigator pairs. The cross-council investigator group outperform their within-council counterparts, as demonstrated by the notable gains in the number of grants and their value; as well as the average team size (Fig. 4c, Supplementary Table 3). For the sake of robustness, we repeat our analyses across different time periods, reaching the same conclusions (Supplementary Figs. 13 and 14). Moreover, we check a different definition of interdisciplinary investigators by examining the number of fields (based on the classification by Microsoft Academic Graph) in which they published, again reaching similar conclusions (Supplementary Note 7). These findings uncover

previously unknown positive aspects of an interdisciplinary research career, providing a much needed optimistic outlook for those who wish to pursue this line of work[14].

## Discussion

In this paper, we compare the careers of interdisciplinary investigators with those of investigators who are tied to a specific discipline. In line with other findings on the rise of interdisciplinary research[9,10], we find that the fraction of cross-council investigators increases steadily during our period of observation. We also find that cross-council investigators sit more centrally than their peers in the academic collaboration network, which in turn provides them with considerable competitive advantage in terms of knowledge brokerage opportunities, but such a competitive advantage does not immediately translate into a higher academic impact in their publications.

There are a number of possible reasons for the comparatively lower impact of projects led by cross-council investigators. It is reasonable to argue that their role as knowledge brokers leads to considerable costs—both in terms of building collaborative relationship and establishing a common language to communicate across disciplines[25]—which may indirectly suppress their productivity. Also, despite a lack of consensus on its overall impact[26,27], a number of studies have shown that interdisciplinary research tends to garner recognition over longer periods of time compared to more specialized research[6,28]. In this respect, we ought to acknowledge that our results may partially be due to the duration covered by our available data, which constrains our analyses to quantify impact with citations received within 5 years of publication. It is plausible that our conclusions about impact may be different over longer time
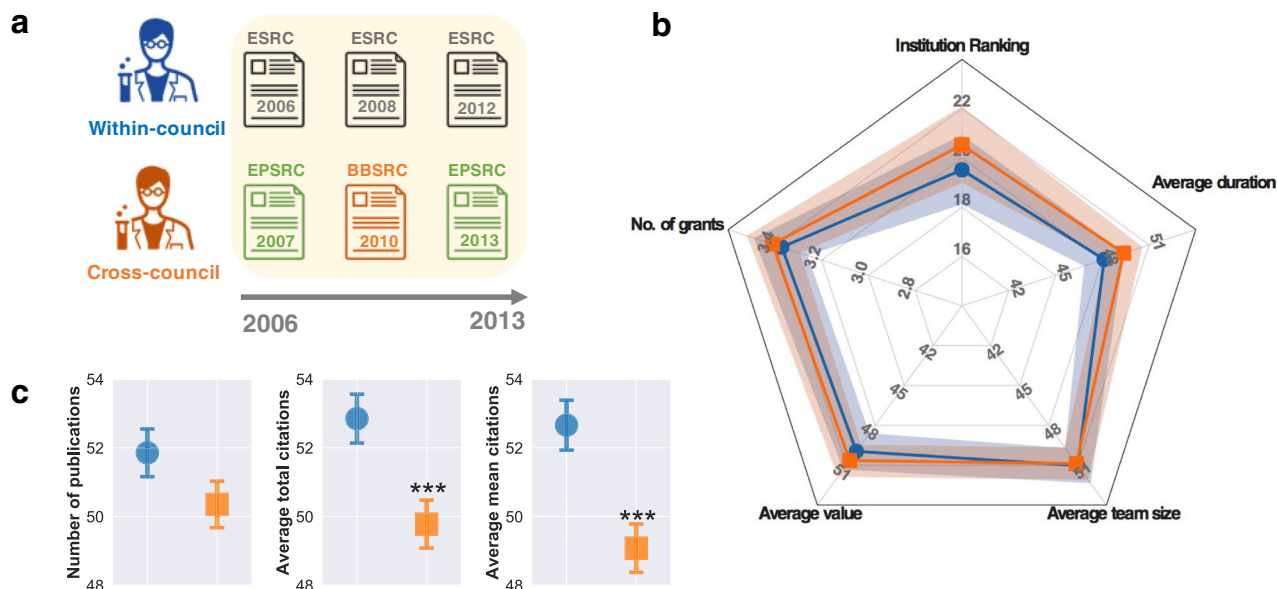
**Fig. 3 Comparing scientific outcomes between cross-council and within-council investigators. a** An illustrative example of cross-council (orange) and within-council (blue) principal investigators (PIs). Both PIs obtained 3 research grants during the observation window from 2006 to 2013, but the within-council PI received grants from the same research council (all three from Economic and Social Research Council (ESRC)), while the cross-council received grants from 2 different councils (two from Engineering and Physical Sciences Research Council (EPSRC), one from Biotechnology and Biological Sciences Research Council (BBSRC)). **b** Matching the cross-council and within-council PIs with similar career profiles in terms of funding performance. We match 5 different characteristics for PIs: institutional ranking of a given PI (whereby institutions are ranked by their total amount of funding between 2006 and 2018), the number of grants a given PI has received, their average grant value, average team size, and average project duration. There is no statistically significant difference between the two groups of PIs across the five dimensions following the pairing. The shaded areas represent 95% confidence intervals. **c** Differences in research outcomes between cross-council and within council PIs on the average number of papers reported per project, the average number of total citations received per grant (calculated as the average of the total citations received by papers associated with a grant), and the average number of citations received per paper per grant (calculated first as the average of the citations received by papers associated with a grant, and then averaged over the total number of grants awarded to a PI). Citations are considered within 5 years after publication, and have been normalized by the average citations of all papers belonging to the same year and discipline in Microsoft Academic Graph dataset. All dimensions considered in panels **b** and **c** (with the exception of institutional ranking and number of grants) are quantified by calculating their percentile rank in the same council and year. The significance levels shown refer to t-tests and Kruskal-Wallis tests. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Error bars represent the standard error of the mean.

periods. This limitation notwithstanding, our findings suggest that it may be very challenging for a junior researcher to pursue an independent interdisciplinary academic career. Indeed, all current practices of academic impact evaluation are to some extent influenced by citation-based bibliometric indicators[29] and, therefore, may be stacked against junior interdisciplinary researchers receiving citations at a slower pace[30].

However, the main result of our study shows that cross-council investigators eventually outperform their peers in terms of funding. This result is robust and statistically significant across different dimensions, with respect to the number of funded grants, the average funded value and the average team size per grant awarded. Although at face value this may seem to contradict previous findings on the lower funding success rate of interdisciplinary research[14], we believe that this is not necessarily the case. Our results primarily focus on the funding performance of investigators in terms of volume and value—not of grant proposals—and do not speak to their success rate, as data about rejected proposals are not available to us. It is therefore possible that interdisciplinary investigators in our data may still secure funding at a lower success rate, although this would directly imply that they submit proposals in much larger numbers than their peers. Furthermore, let us mention that applicants to the vast majority of funding schemes from the UK research councils must hold a permanent position in a research institution in order to act as PIs. In this respect, survival bias does not represent a potential limitation to our analysis, as all the investigators in our data are—by definition—survivors.

All in all, we believe that the more plausible explanation for our findings is that indeed interdisciplinary investigators develop—on average—a better ability to attract funding in the long run. Squaring this with their lower impact in the short run suggests that interdisciplinary investigators may be late bloomers who tend to achieve success over a longer period of time; however, there are indications that their more diversified research portfolios could give them an edge in securing long-term tenure[31].

## Methods

**Data sets.** We collect 44,419 research projects conducted between 2006 and 2018 from UK Research and Innovation (UKRI), which includes the grant information from seven national discipline-based research councils, namely AHRC, BBSRC, ESRC, EPSRC, MRC, NERC and STFC (see Supplementary Note 1). Note that the disciplinary boundaries of the research councils system in the UK are explicitly defined, and an investigator would submit their research proposal to the most appropriate council by checking the remit domains of each possible council. The basic information for each research council has been summarized in Supplementary Table 1. The research grants cover the full spectrum of academic disciplines from the medical and biological sciences to astronomy, physics, chemistry and engineering, social sciences, economics, environmental sciences and the arts and humanities, which enables us to comprehensively investigate research and innovation in the UK. For each research project, we record the information of the title, abstract, the start date and end date, PI and co-investigators (CI), fund value, lead/collaborating institutions and scientific outcomes (i.e., publications). A grant is considered to be awarded to the PI and the affiliation of the PI. Information on how the overall funding of a given grant is divided among the rest of the investigators (and their affiliations) is not made available. Among them, there are 37,677 research projects that have been classified with at least one research subject (a total of 104 subjects). All the research projects, investigators and institutions have been assigned with unique IDs, which eliminates the problem of name disambiguation.
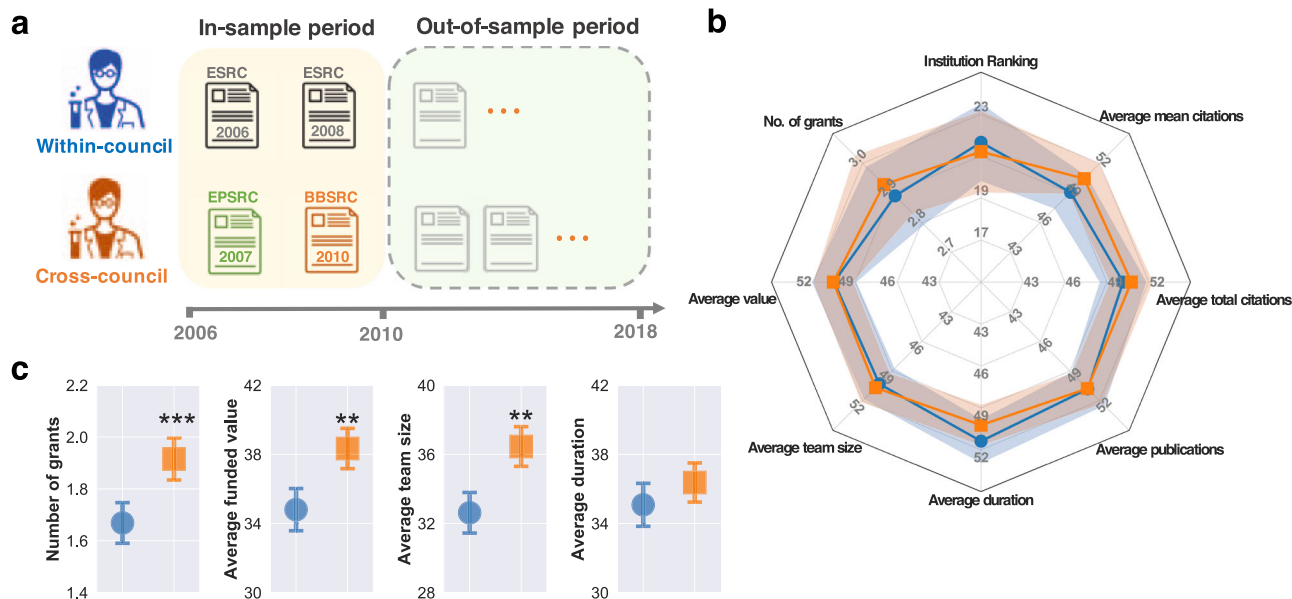
**Fig. 4 Comparing long-term funding performance between cross-council and within-council investigators. a** An illustrative example of comparison in terms of long-term funding performance of cross-council (orange) and within-council (blue) principal investigators (PIs) with similar funding profiles. Both PIs obtained 2 research grants during the in-sample period from 2006 to 2010, but the within-council PI received grants from the same research council (both from Economic and Social Research Council (ESRC)), while the cross-council PI received grants from 2 different councils (one from Engineering and Physical Sciences Research Council (EPSRC), and the other from Biotechnology and Biological Sciences Research Council (BBSRC)). For the in-sample period 2006–2010, we pair the PIs with similar career profiles, while for the out-of-sample period 2011–2018, we compare the funding performance of each paired PIs. **b** Matching the cross-council and within-council PIs with similar career profiles in terms of both funding performance and research outcomes during the in-sample period. We match 8 different factors for PIs between 2006 and 2010 as follows: institutional ranking of a given PI (whereby institutions are ranked by their total amount of funding between 2006 and 2018), the number of grants a given PI has received, their average grant value, average team size, average project duration, average number of publications reported, average number of total citations received per grant (calculated as the average of the total citations received by papers associated with a grant), and the average number of citations received per paper per grant (calculated first as the average of the citations received by papers associated with a grant, and then averaged over the total number of grants awarded to a PI). Citations are considered within 5 years after publication, and have been normalized by the average citations of all papers belonging to the same year and discipline in Microsoft Academic Graph dataset. There is no statistically significant difference between the two groups of PIs across the eight factors following the pairing. The shaded areas represent the 95% confidence interval. **c** Difference in long-term funding performance between cross-council and within-council PIs in the following eight years (2011 to 2018). Cross-council PIs outperform within-council PIs in grant volume, value and team size. The significance levels shown refer to t-tests and Kruskal-Wallis tests. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Error bars represent the standard error of the mean.

For each research grant, all related papers published are recorded with the information of title and DOI. This provides the possibility for us to link the UKRI research grant database with the Microsoft Academic Graph (MAG) database by precisely matching the titles and DOI of the publications in two databases. MAG is a database consisting of a large amount of scientific publications, their citation records, dates of publication, information regarding the authorship, publication venues and more. We wish to point out that the dataset specifies the keywords for each paper, as well as the position of each such keyword in a field-of-study hierarchy, the highest level of which is comprised of 19 disciplines. Therefore, this connection between the two datasets not only offers us additional information about each paper, it also allows us to trace citations of each publication within the MAG and how these citations compare with other papers published in the same year and discipline. In the end, we match a total of 409,546 publications and calculate their accumulated citations 5 years after publication.

**Evolution of cross-council behavior**. In the sliding window analysis, only investigators with at least two research grants have been tracked. We exclude those with one research grant only as they will distort the number of within-council investigators. Supplementary Fig. 1 illustrates the grant history of a cross-council investigator and a within-council investigator. Although the two investigators have obtained the same number of research grants throughout the studied period, their funding trajectories from the research councils are strikingly different.

**Collaboration network**. The collaboration network is constructed by referring project partnerships between investigators between 2006 and 2018. In this network, nodes are investigators (PIs or CIs), and a link refers to a project partnership between two nodes. Research grants comprising only one investigator (i.e. only the PI) have been excluded from the network. We extract the largest connected

component (LCC) of the collaboration network which consists of 86% of the investigators.

We then perform a node-level network analysis on all the investigators who are in the LCC, and only include those with at least 2 research grants during the studied period. In total, we obtain 6911 cross-council investigators and 12,563 within-council investigators. To further test whether this structural advantage exists across different time periods, we examine the collaboration network in the first 5-y window (2006–2010) and last 5-y window (2014–2018) of the available period, and find that our conclusions remain unchanged (see Supplementary Note 5 and Supplementary Figs. 8–9).

**Normalized effective size**. The normalized effective size of node $i$'s ego network measures to which extent each of the first neighbors of $i$ is non-redundant with respect to the other neighbors. Formally, for the case of unweighted and undirected graphs, the normalized effective size of a node $i$ can be defined as[23]:

$$\zeta_i = 1 - \frac{k_i - 1}{k_i} C_i \qquad (1)$$

where $k_i$ is the degree of the node and $C_i$ is its clustering coefficient. This indicator can vary from 0 to 1 with $\zeta_i = 0$ when the neighborhoods of $i$ are fully connected, and $\zeta_i$ taking its largest value 1 when $i$ is the center of a star, and there are no links among its collaborators. Generally, the larger the value of $\zeta_i$, the less connected the neighborhood of $i$ is, and consequently, the higher the brokerage opportunities for investigator $i$. Investigators acting as brokers, on the one hand, tend to exhibit weak ties with their collaborators. On the other hand, they are likely to gain exposure to a greater variance and novelty of information and link people with different ideas and perspectives[32,33].

**Propensity score matching**. To avoid the potential bias of covariates among PIs in the cross-council and within-council groups, we perform a propensity score matching analysis based on multi-variable logistic regression models, which is a statistical technique typically used to infer causality in observational studies[24]. Propensity scores (PSs) are defined as the predicted probability of being a cross-council PI conditional upon a set of observed covariates. Cross-council PIs are matched to within-council PIs based on their PSs in one-to-one ratio, using a nearest-neighbor algorithm within a caliper of 0.01 on the probability scale. After the matching, the characteristics of cross-council and within-council groups in all observed covariates are statistically indistinguishable, with standardized differences $d < 0.1$, t-tests $p$-value > 0.1 for the sample means, and Kruskal-Wallis tests $p$-value > 0.1 for the entire distributions.

## Data availability

## Code availability

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## Author contributions

All authors designed research; Y.S. collected the data and performed research; Y.S., G.L., A.M. and V.L. analyzed data and wrote the paper.

## Competing interests

The authors declare no competing interests.

## Additional information