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Does interdisciplinary research lead to higher citation impact? The different effect of proximal and distal interdisciplinarity

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Abstract

This article analyses the effect of degree of interdisciplinarity on the citation impact of individual publications for four different scientific fields. Rather than treating interdisciplinarity as a monodimensional property, we investigate the separate effect of different aspects of interdisciplinarity on citation impact: i.e. variety, balance and disparity. We use a Tobit regression model to examine the effect of these properties on citation impact, controlling for other variables such as number of authors or organisations. We observe an inverted U-shape relationship between degree of interdisciplinarity and citation impact. We also find that variety has a positive effect on impact, whereas balance and disparity have a negative effect. These findings can be interpreted in two different ways. On the one hand, they are consistent with the view that, while combining multiple fields is good for reaching higher impact, successful research is better achieved through research efforts that draw on a relatively proximal range of fields with only a small proportion of contributions from distant fields - as distal interdisciplinary research might be too risky and more likely to fail. On the other hand, these results may be interpreted as suggesting that scientific audiences are reluctant to cite heterodox papers that mix many disparate bodies of knowledge ? putting at a disadvantage publications that are purposefully challenging.

Jelcodes:O21,O29

Does interdisciplinary research lead to higher citation impact? The different effect of proximal and distal interdisciplinarity

1. Introduction

The last decades have seen a surge on interdisciplinarity in science policy discourse, as well as an increase in the explicit promotion of interdisciplinary research (IDR)[1] virtually across all scientific fields (Jacobs and Frickel, 2009, pp. 45-46; NAS, 2005; Braun and Schubert, 2003). Promotion policies have included programmes specifically funding 'interdisciplinarity' via match-making events such as the National Academies Keck Futures Initiative (NAKFI, www.keckfutures.org/, Porter et al., 2006), via graduate programmes such as the Integrative Graduate Education and Research Traineeship (IGERT, www.igert.org, see Rhoten et al., 2009). More widely, interdisciplinarity has been seen as a highly positive criterion for the most prestigious, high-risk/high-reward grants. A prominent example of the latter are the grants of the new European Research Council (ERC), which 'aim to support 'Frontier Research', i.e. 'proposals of an interdisciplinary nature which cross the boundaries between different fields of research', 'addressing new and emerging fields' or 'introducing unconventional, innovative approaches and scientific inventions' (ERC, 2010, p.12).

In this context, there has been a demand for social scientists to justify the opportunity of the initiatives supporting IDR. The assumption underlying these policies is that IDR brings forth more scientific breakthroughs, fosters innovation and helps address societal problems[2]. However, there is little systematic evidence showing that IDR is 'better' on its own sake and hence should be specifically funded or promoted by policies that counter or assuage the

[1] We do not make the difference between multi-, inter- or transdisciplinarity, which were proposed as terms to differentiate between low and high levels of integration. We use interdisciplinarity as a general term encompassing all forms of disciplinary crossings.
[2] We would argue that IDR is also viewed positively because it is congruent with the *zeitgeist* of our time, what Zygmunt Bauman calls *liquid modernity* (Baumann, 2005), which embraces hybridization, deterritorialization, nomadism, diasporism or outsiderness (Hoffmann, 1999, pp. 44-45).

‘disciplining’ pressures of disciplines. On the one hand, there are indeed many narratives of successful research, and particularly, major breakthroughs that resulted from IDR (e.g. see Hollingsworth and Hollingsworth, 2000, on discoveries in the Rockefeller Center). But there are also plenty of examples of unsuccessful IDR –which are less reported, but not unnoticed by science managers and policy-makers. Hence, one should not jump to the conclusion that overall science would improve if research were more interdisciplinary. Evidence on whether IDR is more or less successful is scarce, messy and inconclusive.[3] This has led a number of scholars to take a sceptical stance on the ‘superiority’ of IDR, e.g. Jacobs and Frickel (2009, p. 44):

> *‘The widespread attention that administrators, funders and faculty alike are giving to interdisciplinarity -and the intensity of the debates that attention has generated- is striking given the fact that relatively little research on many of the underlying issues has been conducted.’*

The lack of univocal results on the benefits of IDR stems from the multiplicity of possible perspectives (and associated ambiguity) on both the benefits of research and the concept of interdisciplinarity (e.g. Huutoniemi et al., 2010). The societal impact of research is an extremely controversial and politically heated issue that goes beyond the scope of our study (Salter and Martin, 2001; Spaapen et al. 2007; Spaapen and van Drooge, 2011). While acknowledging this plurality, here we aim to investigate the issue by restricting our attention to internal scientific dynamics, looking into the relationship between citation impact of a publication and its degree of IDR using bibliometric methods.

Following established methodology, citation impact can be operationalised in terms of number of citations after field-normalisation. However, the bibliometric operationalisation of IDR remains contentious (Morillo et al., 2003; Huutoniemi et al. 2010; Wagner et al. 2011). Here we adopt the conceptualisation of IDR as diversity of cited disciplines (Rafols and Meyer, 2010).

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[3] Equally, the same lack of conclusive evidence is found about the benefits of diversity at every level (nation, city, groups, etc.) (Page, 2007, pp. 12-15).

The key innovation of this article is that instead of creating a ‘composite’ indicator of IDR, we investigate separately how each of the attributes of diversity (namely: *variety*, *balance* and *disparity* of disciplines; see Stirling, 2007) affects the impact of a publication. The evidence obtained from regression analysis shows that each of these attributes has a different effect on the publication impact. The results suggest that the most cited publications are those with a *clear disciplinary focus*, but that nevertheless give *small proportions of references* to many proximal disciplines.

The paper is organized as follows. Section 2 describes benefits and costs associated to interdisciplinary research. Section 3 presents a review of the literature dealing with the relationship between interdisciplinarity and citation impact. Section 4 introduces the conceptualization of interdisciplinary research used in this study. In Section 5 are described the data, measures and methods. Section 6 contains the results and Section 7 presents the discussion.

2. Benefits and costs of interdisciplinary research (IDR)

Whether explicitly or not, the debate on IDR has a subjacent normative loading: interdisciplinarity is brought into the table precisely because it is perceived as precious, yet missing. As a result, an ample literature discusses the benefits of interdisciplinarity, although most often from a ‘normative and speculative’ rather than analytical perspectives (Weingart, 2000, p. 31).

First, it is argued that IDR is more successful at problem solving and prediction: most specific problems do not fit into disciplinary silos but are best tackled by combining diverse epistemic approaches. Scott Page (2007) provides a sophisticated theoretical argumentation on why ‘diversity trumps ability’, i.e. on why the combination of diverse perspective, interpretations, heuristics and/or models is better than ‘excellent’ but narrow skills at problem-solving. Building on insights from science and technology studies, Stirling (1998, pp. 14-36) also argues that solving complex social problems is best achieved via cognitive diversity, which helps in hedging against ignorance (e.g. unexpected 'unknowns'), mitigating socio-technical lock-ins, and accommodating plural perspectives. This rationale for IDR is thus particularly strong and convincing in scientific programmes addressing grand societal issues or challenges, such as climate change, epidemic disease, preservation of biodiversity, or innovation-led economic growth, etc., which have become more salient with increasing accountability of science (see Lund Declaration, EU, 2009; Gibbons, 1999).

Empirical studies support this link between societal problem solving and interdisciplinary research. Van Rijnsoever and Hessels (2011) report more propensity for IDR collaborations for researchers that (i) have experience outside academia; and (ii) work in strategic rather than basic disciplines (i.e. in the Pasteur quadrant of fundamental research associated with visions of applications). Similarly, Carayol and Thi (2005) provide evidence of correlation between degree of IDR and industrial links (either collaborations or contractual). Second, IDR is seen as beneficial since it generates new research avenues and 'rejuvenates' the landscape of science. From an evolutionary and ecological understanding of the science system, IDR is the key mechanism to create via recombination the variations necessary for the system to evolve.

Third, Barry et al. (2008, p. 29) argue that this dynamics does not always result only from integration of hitherto unconnected fields but that IDR also 'springs from a self-conscious dialogue with, criticism of or opposition to the intellectual, ethical or political limits of established disciplines, or the status of academic research in general'. In other words, IDR is born out of intentional struggles for broadening perspectives and it is thus seen a source of pluralism (Corsi et al., 2010; Phillips, 2009; Willmott, 2011).

In spite of these benefits, it is now widely acknowledged that conducting IDR entails important efforts, which hinder the chances of success and we will call metaphorically 'costs', following the introduction of this insight by Katz and Martin (1997). Two types of costs can be distinguished: those associated with coordination (or 'transaction') and those arising from institutional pressures against IDR.

Coordination costs result from the difficulties of integration and they are common to team management or collaborations in general (Cumming and Kiesler, 2005; Rafols, 2007). Though IDR does not necessarily entail diverse teams or collaborations, it often does. Coordination costs include: efforts to overcome the lack of a common language, shared meanings and norms within diverse teams; negotiations to harmonize differences in the management and organisational cultures of the collaborating organisations (e.g. on rules of graduate student exchange); administrative load and time needed to manage 'distributed' research; expenses to travel over geographical distance. *Institutional costs* or barriers against IDR arise because of the institutionalisation of science in terms of disciplines. By definition, the functions of disciplines is to 'discipline disciples' and to suppress or marginalise methods, objects and concepts that do not abide to their disciplinary standards (Barry et al. 2008, p. 20). In spite of the pro-IDR rhetorics of science policy, the norms and rules that govern the scientific enterprise in the everyday management of universities, conferences, recruitment, journals, peer-review, etc. strongly favours mono-disciplinary approaches. Turner (2000) attributes the institutional dominance of disciplines to the labour-market structure, whereupon PhD granting departments, disciplinary association meetings and undergraduate teaching generate a self-reproductive pattern. Abbott (2001, p. 135) adds to this argument, the intellectual advantage of the main (abstract) disciplines of creating 'problem-portable' knowledge, i.e. knowledge that can be re-used for a variety of problems. Bruce et al. (2004, p. 464) reported the following institutional costs from interviews on IDR collaboration: poor career structures for academic interdisciplinary researchers; low esteem by colleagues; difficulty to publish in high ranking journals; discrimination by reviewers in proposals.

Evidence of unclear career for IDR students is supported by Carayol and Thi's (2005) finding that PhD and junior researchers were the least likely to engage with IDR. Even in areas with an interdisciplinary (and ideological) ethos such as environmental sciences, committed IDR students reported that they envisaged 'to pay a price' for it in their future employment opportunities (Rhoten and Parker, 2006). Van Rijnsoever and Hessels (2011) found that collaborations within disciplines contribute more to career advancement than interdisciplinary ones. The causal mechanisms by which engaging in IDR research hinders career advancement may be more complex. For example, it is well known that women have a higher propensity to conduct IDR (Rhoten and Pfirman, 2007; van Rijnsoever and Hessels, 2011). Rigorous quantitative analysis by Leahey (2007) shows that this is one of the factors explaining why women earn less than men in academia: 'largely because they specialize less [in disciplines]. Lower levels of specialization hinder productivity, productivity enhances visibility, and visibility has a direct, positive, and significant effect on salary' (p. 533).

Bias in evaluation is another major concern of researchers conducting IDR. That evaluation of IDR is problematic should not be a surprise. Any evaluation needs to take place over established standards. These standards can be defined within a discipline[4], but what standards should be used for IDR? This is a topic that has received considerable attention (see monographic issue of *Research Evaluation,* edited and introduced by Laudel and Origgi in 2006, and a recent literature review by Klein, 2008; also Rafols et al., 2012 for quantitative evidence on bias). A variety of studies have found that what happens, even in the case of multidisciplinary panels, is that IDR ends up being assessed on disciplinary perspectives (Mallard et al., 2009).

The above discussion suggests that IDR benefits are eminently epistemological (i.e. better ways of solving problems, challenging established approaches and nurturing the creation of new knowledge), whilst we can locate the costs in the social sphere (coordination costs) and the institutional settings (institutional costs by disciplines). The extent to which the costs of IDR outweigh the benefits is a matter of open debate and empirical research. Some authors, such as Llerena and Meyer-Krahmer (2004) and Cummings and Kiesler (2005), have suggested that there is an inverted-U shape relationship between IDR and scientific impact: conducting IDR may entail positive rewards in terms of contribution to knowledge (and scientific impact) up to a given threshold beyond which further levels of IDR may cause too high coordination and

[4] In fact, even within a discipline, the standards will be those of the dominant community –thus marginalising peripheral and less 'pure' approaches.

institutional costs for those engaged in interdisciplinary research. In the following section we review the empirical evidence on the relationship between IDR and scientific impact, to shed some light on this matter.

3. Evidence on the effect of interdisciplinarity on citation impact

During the last years several studies, have analyzed the effect of interdisciplinary research on research performance. The difficulty of carrying out this type of investigation is due to the fact that both interdisciplinarity and performance are complex, multidimensional and thus controversial properties. The relationship between these interdisciplinarity and citation impact has been tested at different levels of analysis (mainly either at the article or journal level). The most frequent data source was the Web of Science (WoS). The WoS Categories (which were known as ISI Subject Categories up to WoS version 4) have been usually used to operationalize the notion of interdisciplinarity in many previous studies (Rinia et al., 2001).

However, these previous studies not only report different effects of interdisciplinarity on citation impact but they also differ in other methodological aspects that might have influenced the achievement of these conflicting results. In fact, different indicators have been used to capture interdisciplinarity showing somehow the existing lack of consensus on IDR measures (Wagner et al., 2011). It is also possible to perceive some variety among the indicators of citation impact; however most of studies rely in relative indicators, normalizing the citation counts by field.

For instance, Steele and Stier (2000) estimated the degree of interdisciplinarity through the Brillouin's diversity index (related to Herfindhal's) and they found a positive and significant effect on the citation impact. However, Rinia, van Leeuwen, van Buren and Van Raan (2001) found no significant correlation between the degree of interdisciplinarity and citation impact, measuring the degree of interdisciplinarity as the proportion of papers published by physicists in disciplines other than physics.

More recently, a report to the Higher Education Funding Council for England (Adams, Jackson and Marshall, 2007) tackled the relation between interdisciplinarity, operationalised as the entropy measure based on the number of disciplinary categories in articles, and the amount of received citations by papers, reporting no tendency for the most insterdisciplinary papers to be less cited, but without a robust quantitative proof. Adams et. (2007) also suggest from visual inspection that those articles with highest citation rates recorded an intermediate level of interdisciplinarity.

Levitt & Thelwal (2008) found that citation levels to multidisciplinary journals (those related to more than one disciplinary category in the database) were roughly 50% less than monodisciplinary articles. This correlation was found using Scopus as data source and only for a number of limited science disciplines. When the analysis was focused on the social sciences neither in Scopus nor Web of Science were significant correlations found between the level of interdisciplinarity and the citation impact.

Table 1. Studies analyzing the relationship between interdisciplinarity - citation impact.

	Steele & Stier (2000)	**Rinia et. al (2001)**	**Adams et. al. (2007)**	**Levitt & Thelwall (2008)**	**Lariviere & Gingras (2010)**
Sample	750 articles in the area of forestry (period 1985-1994)	All academic groups in physics the Netherlands	Articles from two UK universities	All science and social science articles	All papers published in WoS in 2000
Database	*Journal Forest Science*	WoS	WoS	WoS and Scopus	WoS
Unit of analysis	Article	Journal	Article	Journal	Article
IDR Indicator	Brillouin's diversity index	% papers not published in the field of physics	Shannon Diversity % cited refs. to other SC	Number of disciplines assigned to journals	% cites refs. to other SC
Aspect of diversity	Combination of variety and balance	Balance	Variety and Balance	Variety	Balance
Measure of citation impact	Average annual citation rate	Normalized indicators	Normalized indicators	Normalized indicators	Normalized indicators
Correlation IDR vs Impact	Positive	No effect	Moderate evidence of inverted U	No effect in SS in some disciplines	Inverted U shape

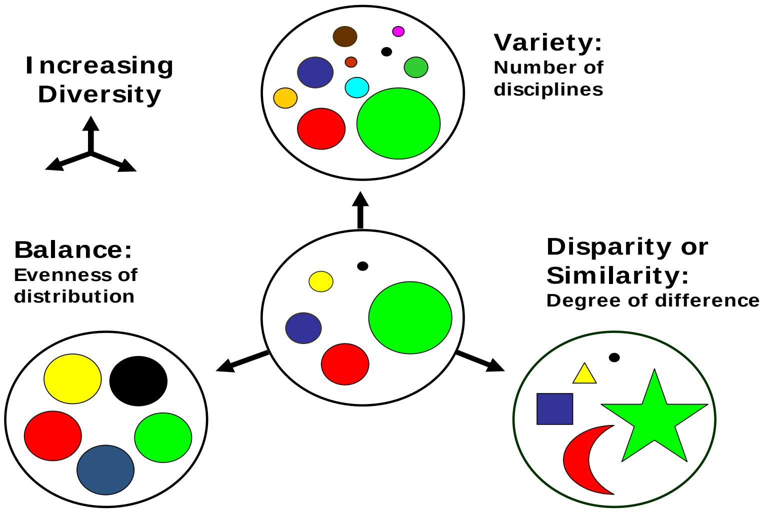
The study developed by Larivière, V. & Gingras, Y. (2010) did not find a clear correlation between the proportion of citations to other disciplines (their indicator of interdisciplinarity) and the citation received for an analysis of all the articles included in Web of Science in 2000. The key finding of these authors was that in all disciplines those articles with a low citation rate were highly disciplinary or highly interdisciplinary, suggesting that there might be an optimum level of interdisciplinarity. Table 1 summarizes the methods and results achieved so far by these studies.

4. A multidimensional conceptualisation of IDR: variety, balance and disparity

The literature review presented above shows both the variety of existing indicators to measure the notion of interdisciplinary research and their lack of comprehensiveness in capturing the whole idea of this notion, i.e. indicators inform about variety and/or balance but disparity is usually not measured. We try to overcome some of these drawbacks by adopting a conceptualisation that enables us to tackle the different dimensions involved in the concept of interdisciplinary research (Rafols and Meyer, 2010).

Let us begin by stating that here we adopt a definition of interdisciplinarity based on the central concept of integration: a mode of research that *integrates* concepts or theories, tools or techniques, information or data from different bodies of knowledge (National Academies, 2005; Porter et al. 2006, p. 3). In order to capture the process of integration, i.e. the process in which previously different and disconnected bodies of research become related, we rely on the concept of diversity as proposed by Stirling (2007) and illustrated in Fig.1.

Figure 1. Schematic representation of the attributes of diversity, based on Stirling (2007).



This concept refers to three different attributes of a system comprising different categories: (i) Variety: number of distinctive categories; (ii) Balance: evenness of the distribution of categories; (iii) Disparity or similarity: degree to which the categories are different/similar. An increase in any of these attributes results in an increase in the diversity of the examined system.

Indicators aiming at capturing the degree of diversity in studies of interdisciplinarity (i.e. disciplinary diversity) rely on the established disciplinary classifications (e.g. WoS-Categories in the Web of Science) so that *variety* refers to the number of disciplines, *balance* is related to the evenness of the distribution of disciplines and *disparity* measures the extent of which these disciplines are different/similar from a cognitive point of view.

We have calculated these three different aspects of disciplinary diversity as follows:

Variety: Number of distinctive disciplines (n) cited in an article.

Balance: This dimension is calculated on the basis of the Shannon Diversity Index (H), where p_i is the proportion of references in discipline i:

$$\text{Balance} = -\frac{1}{\ln(\text{n})}\sum_i p_i \ln p_i$$

Disparity: we calculate the cognitive distance between two disciplines as the opposite of the average cognitive similarity between disciplines (d_{ij}=1-s_{ij}, with s_{ij} being the cosine similarity between each pair of disciplines *i* and *j*).

$$\text{Disparity} = \frac{1}{n(n-1)}\sum_{ij} d_{ij}$$ (considering all disciplines with at least one cited reference)[5]

The implementation of these three different indicators aims at capturing and isolating each dimension of diversity. This approach enables us to analyse to what extent these dimensions provide a distinctive insight about diversity and to examine if they have a distinct influence on citation impact.

5. Data and methods

5.1. Data

We collected publication data corresponding to original articles and proceedings papers published in 2005 from Science Citation Index-Expanded (SCI-E) belonging to four WoS-Categories i.e. Cell Biology (CBIOL), Engineering, Electrical & Electronic (EEE), Food Science and Technology (FSTA) and Physics, Atomic, Molecular & Chemical (Physics-AMC). These four fields cover to some extent, the spectrum of applied and fundamental research, ranging from physics to engineering, and encompassing biology research. The total number of collected papers amounts to 72,116 records (CBIOL n=16,922; EEE n=30,574; FS&T n= 10,869; Physics-AMC n=13,751). However the final dataset comprises 62,408 papers, due to selection of papers with sufficient references to apply the measure of interdisciplinary diversity, as we explain below.

[5] See Section 5.2 below for further details on how we computed these distances.

5.2 Measures

5.2.1 Dependent Variable

We have measured citation impact in terms of normalized number of citations, taking into account the scientific field, the publication year and the document type. For each paper, the procedure of such normalization consists of dividing the actual number of citations received by the world average number of citations per paper in the same field, published in the same year and belonging to the same document type. We used a fix citation window of five years.[6]

5.2.2 Independent variables: variety, balance and disparity

In order to calculate disciplinary diversity, we consider disciplines related to the reference list in a given paper. Our assumption is that the citing paper *integrates* knowledge from the disciplines to which the cited papers belong. In order to operationalize this idea, we considered the distribution of WoS-Categories in the references cited by the papers in our sample. We obtained the distribution of WoS-Categories by transforming the list of journals in which the references were published into a list of Web of Science Categories according to the Journal Citation Reports.

In order to have a notion about the disciplinary scope of a paper we decided that it would be necessary to have a minimum of four references linked to at least one discipline.[7] Hence we removed from our sample those papers below this threshold.[8] The total amount of deleted papers was 9,708 (CBIOL n=161; EEE n=8,351; FS&T n=832; Physics-AMC n=364). Table 2

[6] This is done to avoid the possibility of receiving a higher number of citations for the oldest articles compared to the most recent articles in our sample. According to Moed (2005), the time horizon applied should not be too short as it takes some time for an article to demonstrate its importance and receive citations; a citation window of 3 o 5 years following the year of publication has proven to yield the most informative trend data, that is why we chose a five year citation window in calculating the normalized citation impact.

[7] Given the multi-assignation a unique reference may be linked to more than one discipline

[8] Actually it is possible to distinguish two sets of papers among those removed. The first set comprises papers citing fewer than four references and the second set is integrated by papers citing more than three references, but for which it was only possible to link three or less references to at least one discipline, probably because they cite document types other than journal articles or journals not covered by the WoS.

presents some statistics on the number of papers, references and linked references to WoS-categories per disciplines, both for the original and the final sample.

Table 2. Descriptive data.

Original sample					
	Papers	**References**	**Median**	**Mean±SD**	**% Linked**
CBIOL	16,922	702,305	40	41.50±17,48	93.27%
EEE	30,574	518,116	14	16.95±12.08	50.00%
FS&T	10,869	288,026	25	26.50±15.19	73.66%
Physics-	13,751	437,328	28	31.80±18.10	81.00%
Total	72,116	1,945,775	23	26.98±18.10	76.10%
Final sample					
	Papers	**References**	**Median**	**Mean±SD**	**% Linked**
CBIOL	16,761	701,832	40	41.87±17.14	93.32%
EEE	22,223	447,660	17	20.14±12.12	55.23%
FS&T	10,037	284,069	26	28.30±14.27	74.41%
Physics-	13,387	435,101	29	32.50±17.82	81.25%
Total	62,408	1,868,662	26	29.94±17.50	78.51%

After deleting those articles with fewer than four references linked to WoS categories, the final dataset included 62,408 articles citing 1,868,662 references, and the overall share of references linked at least to one discipline is 78.51%. This can be considered a high percentage since Lariviere & Gingras (2010) found the highest scores in medical fields where these authors linked around 79% of cited references to a WoS-Category.

The distribution of SCs in the reference list allowed us to compute *variety*, *balance* and *disparity* as described in section 4: *variety* as the number of SCs (n) that appeared at least once and *balance* as the evenness of the distribution of SCs. In order to compute the *disparity* measure, a similarity matrix s_{ij} for the SCs must be constructed. To do so, we created a matrix of citation flows matrix between SCs, and then converted it into a Salton's cosine similarity matrix in the citing dimension. The s_{ij} describes the similarity in the citing patterns for each pair of SCs in 2006, for the SCI set (175 SCs). A detailed description and analysis of this sij SC-similarity matrix is provided elsewhere when describing global maps of science (Rafols et al., 2010). See descriptive statistics for all these variables in the Table (3) below.

5.2.3 Control variables

In order to account for a number of characteristics of publications that the literature has considered as potentially associated with number of citations per paper, we have included the following control variables. First, the number of authors (*n_authors*) and the number of institutions in the publication (*n_inst*). Second, we have controlled for the geographic scope of the collaboration by building a set of three dummy variables. *National_collab* takes value 1 if there are at least two different institutions in the paper, all of them belonging to the same country. *Internat_collab* takes value 1 if the paper has been produced in collaboration between two or more different countries. And *No_institutional_collab* that takes value 1 if only one institution participates in the paper. This is aimed to capture whether collaborating with foreign institutions exert a positive effect on citation impact. Third, we have constructed a dichotomous variable to control for whether the paper belongs to each of the four WoS-Categories considered in this analysis (i.e. CBIOL, EEE, FSTA or Physics-AMC).

Table 3 below provides the descriptive statistics and Table 4 the correlation matrix for all the variables used in the analysis. Table 4 shows that there is a low correlation between our independent variables (i.e. variety, balance and disparity), providing a first descriptive evidence that they reflect different vectors of interdisciplinarity, and are worth considered separately rather than brought together in a combined index. We will next examine whether these three dimensions of IDR contribute to achieve higher citation impact as well as identifying to what extent these three attributes of diversity have a distinct effect on citation impact.

Table 3 Descriptive statistics (Number of observations: 62,408)

	ln(citations	Variety	Balance	Disparity	n_authors	n_inst.	No_coll.b	Nat._coll.	Inter._coll.
Average	0.554	0.250	0.812	0.581	4.232	2.062	0.402	0.381	0.212
Stand. Dev.	0.471	0.140	0.141	0.149	2.719	1.284	0.490	0.486	0.409
Median	0.455	0.235	0.835	0.598	4.000	2.000	0.000	0.000	0.000
Minimum	0.000	0.029	0.000	0.024	0.000	0.000	0.000	0.000	0.000
Maximum	4.777	1.000	1.000	1.000	226.000	38.000	1.000	1.000	1.000

Table 4. Correlation matrix (Number of observations: 62,408)

	ln(citations)	Variety	Balance	Disparity	n_authors	n_inst.	No_Coll.	Nat_col.
Variety	0.070*							
Balance	-0.053*	0.148*						
Disparity	0.019*	0.185*	-0.222*					
n_authors	0.087*	0.222*	0.048*	-0.065*				
n_inst	0.095*	0.200*	0.030*	-0.016*	0.590*			
No._Coll.	-0.060*	-0.135*	-0.022*	0.002	-0.354*	-0.679*		
National_coll.	0.002	0.112*	0.030*	-0.008*	0.179*	0.342*	-0.644*	
Internat_coll.	0.076*	0.037*	-0.011*	0.010*	0.218*	0.426*	-0.425*	-0.407*

* $p < 0.05$

It is important to note that the distribution of citations per article is skewed. About 10% of the 62,408 (i.e. 6,107) articles did not receive any citation in the five-year window considered in this study and 50% receive less than 7 citations (with a maximum of 782 citations). Median of citations per paper vary among disciplines (12 in CBIOL, 6 in Physics-AMC, 5 in FS&T and 4 in EEE) as well as percentages of not-cited articles (15.42% in EEE, 10.52% in FS&T, 7.75% in Physics-AMC and only 3.5% in CBIOL). Given these differences in the citation patterns among disciplines it is necessary to normalize by field in order to make comparisons.

Given that our dependent variable (normalized number of citations) is a ratio with a lower boundary at zero and a upper boundary at infinity and a significant proportion of the observations in our sample are zeros (i.e. about 10% of publications receive no citations), we have used a Tobit regression model to account for the disproportionate number of observations with zero values, and avoid inconsistent estimates from Ordinary Least Square (OLS) regression.

6 Results

This Section reports the results of our analysis about the effects of interdisciplinary research on citation impact. Table 5 reports the results of Tobit estimates for the whole sample (i.e. 62,408 observations). We present the results in four columns: the first column shows the linear effects of each of the diversity measures on our normalized measure of citation impact, while the other three columns display whether there is evidence of a curvilinear relationship, by introducing the quadratic effect for each of the diversity measures in turn.

Table 5 shows that the three aspects of diversity have a statistically significant and distinct effect on citation impact. While variety has a positive effect on citation impact, balance and disparity have a negative effect on the citation impact of publications. Therefore, the number of different scientific fields a publication draws upon has a strong positive effect on the citation impact, but this effect can be outweighed by the effects of too high a distance between the scientific fields (high disparity) or too much distribution across scientific fields (high balance).

The second important result from Table 5 is that all the quadratic terms are statistically significant and negative. For all three diversity measures, the results from Table 5 indicate the presence of a curvilinear inverted U-shape between each of the diversity measures and the citation impact of publications. This curvilinear relationship indicates that, while variety, balance and disparity have an initial positive effect on the citation impact of publications, a threshold is reached beyond which higher levels of diversity might be detrimental to the citation impact of publications. It is interesting to note, however, that such threshold differs for each of our three measures of diversity. For instance, while the maximum level of impact in the case of variety is reached when variety takes values around 0.52, this threshold is 0.44 in the case of balance and 0.29 in the case of disparity. The curvilinear relationship is illustrated in Figure 2 (see plots 2.a, 2.b, and 2.c), showing the inverted U-shape relationship for each of the three aspects of diversity.[9]

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[9] We replicated the analysis for our four scientific fields: Cellular Biology (CBiol), Electrical and Electronic Engineering (EEE), Physics (PHY) and Food Science and Technologies (FST). These results are overall consistent with those obtained for the complete sample. In particular, we observe that the three aspects of diversity have all a significant effect on the citation impact of publications, and with a similar sign to that obtained for complete sample (with minor exceptions). Moreover, we also observe that the curvilinear inverted U-shape relationship does generally apply for most of the cases in which a quadratic term is introduced in the regression analysis. These results have not been included in the paper but are available from request to the authors.

A further interesting observation is related to the maximum levels for variety, balance and disparity. In the case of variety, the optimum is achieved for a value well above the average level of variety in our population of papers; thus, we could interpret this as an indication that papers should have exhibited higher variety to improve their citation performance. However, balance and disparity have an optimum that is lower than the mean of the empirical distribution – which suggests that most papers were actually citing more evenly and farther away in cognitive distance than they should have done in order to achieve the highest citation impact. Figure 2 provides the plots of the relationships between the estimated values of citation impact and our three measures of diversity, together with the three histograms for variety, balance and disparity (see 2.d, 2.e and 2.f).

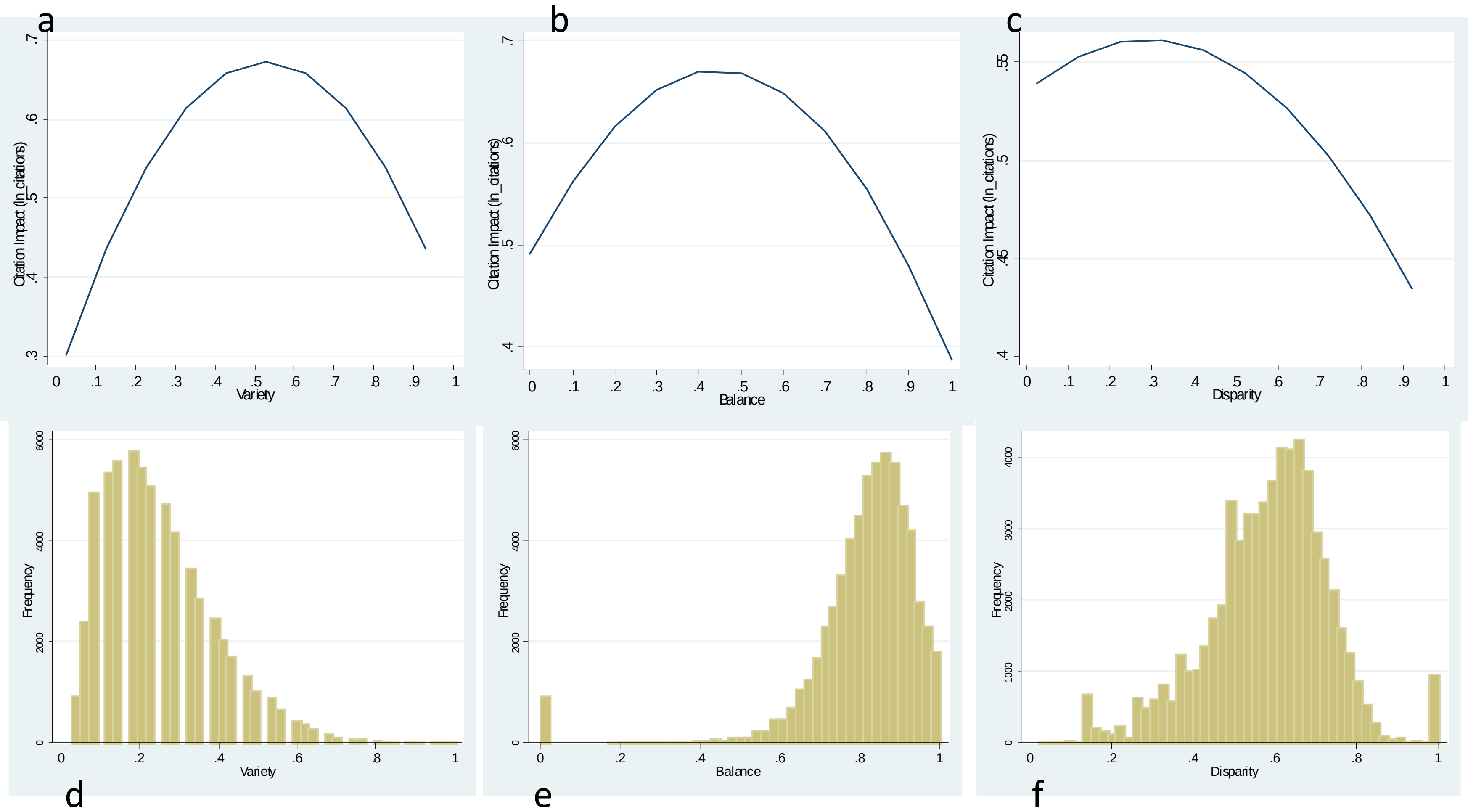
Similar to previous studies, we have found that citation impact is positively and significantly shaped by: the number of authors and the number of institutions involved in a paper. However, we have found a weak or no support for the impact of international collaborations on the citations received by a paper.

Table 5. Tobit estimates for the effect of variety, balance and disparity on citation impact

	Dependent variable: *ln(citations)*			
Variables	(1)	(2)	(3)	(4)
Variety	0.563 ***	1.564 ***	0.473 ***	0.558 ***
	(0.019)	(0.056)	(0.020)	(0.020)
Balance	-0.328 ***	-0.387 ***	0.817 ***	-0.360 ***
	(0.016)	(0.016)	(0.054)	(0.017)
Disparity	-0.162 ***	-0.197 ***	-0.042 **	0.183 **
	(0.017)	(0.017)	(0.017)	(0.072)
$Variety^2$	---	-1.482 ***	---	---
		(0.078)		
$Balance^2$	---	---	-0.921 ***	---
			(0.041)	
$Disparity^2$	---	---	---	-0.317 ***
				(0.064)
N_authors	0.018 ***	0.018 ***	0.017 ***	0.014 ***
	(0.001)	(0.001)	(0.001)	(0.001)
N_Institutions	0.010 ***	0.011 ***	0.010 ***	0.011 ***
	(0.003)	(0.003)	(0.003)	(0.003)
Internat_collab	0.011	0.008	0.009	0.016 **
	(0.007)	(0.007)	(0.007)	(0.007)
National_collab	0.001	-0.001	0.003	0.005
	(0.006)	(0.006)	(0.006)	(0.006)
CBiol	-0.134 ***	-0.141 ***	-0.114 ***	-0.128 ***
	(0.007)	(0.007)	(0.007)	(0.007)
EEE	0.060 ***	0.088 ***	0.085 ***	0.067 ***
	(0.006)	(0.006)	(0.006)	(0.006)
FST	-0.026 ***	-0.022 ***	-0.019 ***	-0.022 ***
	(0.007)	(0.007)	(0.007)	(0.007)
Constant	0.611 ***	0.544 ***	0.244 ***	0.559 ***
	(0.018)	(0.019)	(0.025)	(0.022)
N. obs.	62406	62408	62408	62408
Log-Likelihood	-46917.4	-46737.0	-46668.2	-46896.7
LR X^2	3696.46 ***	4057.23 ***	4194.63 ***	3737.9 ***
McFadden Pseudo R^2	0.04	0.04	0.04	0.04

Notes: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Standard errors are in parenthesis. 9 dummies have been included in the regression to account for the effect of countries (from the authors' affiliations) in the number of citations received. These dummies are not reported in the Table.

Figure 2. Relationship between the estimated values of citation impact and each of the three aspects of interdisciplinary diversity/ Histograms



7. Discussion and conclusions

The results obtained suggest that the publications that accrue the most citations are moderately interdisciplinary, in accordance with some previous studies (Lariviere and Gingras, 2010). Our study contributes to previous articles because it develops more robust indicators of interdisciplinarity (including cognitive distance) and it uses a regression analysis which allows to control for the effect of other variables such as number of authors or organisations, which might have an effect in citation impact. A further finding is that all three dimensions of IDR (i.e. variety, balance and disparity) display a curvilinear relationship with citation impact. In other words, there is an inverted U-Shape relationship between citations received for the number of Web of Science categories cited (variety), for the distribution of references (balance) and for the cognitive distance of the references (disparity). This means that there is a threshold level beyond which more of any of the different aspects of IDR may be detrimental to citation impact.

The second, possibly more interesting finding, is that while the optimum for variety is higher than the mean variety empirically observed, the optimum level of balance and disparity is lower than the mean values currently observed. The key new insight of this study is thus, that highly cited papers tend to cite various disciplinary categories, but cite those outside the disciplinary vicinity in small proportions (lower balance than the average). Put in opposite terms: bold interdisciplinary papers that draw on disparate disciplines in a balanced way (distal interdisciplinarity) are very unlikely to become highly cited. In everyday terms, we might say that practicing ‘meek’ or ‘shy’ interdisciplinarity pays off, but brazen, audacious interdisciplinary efforts are not rewarded with citation success.

In short, we have shown that interdisciplinary research has a significant effect on the number of citations received by a paper, but it is crucial to highlight that the various aspects of diversity are likely to push in opposite directions.

The key finding of this study is that variety (number of fields) has a positive effect on impact, whereas balance and disparity have a negative effect. This finding can be interpreted in two different ways. On the one hand, it is consistent with the view that successful research is achieved in scientific efforts clearly positioned in a given field and nearby areas (proximal interdisciplinarity) with only a small proportion of contributions from distant fields, whilst distal interdisciplinary research is too risky and tends to fail. On the other hand, it may be interpreted as suggesting that scientific audiences are reluctant to cite heterodox papers that mix many disparate bodies of knowledge –putting at a disadvantage publications that are too challenging.

Therefore these findings need to be taken with a note of a caution on their interpretation in science policy context. The measure of performance used (number of citations) only refers to citation impact (missing broader societal benefits) and is a proxy of ‘perceived’, but not factual, scientific quality. Further research is needed to investigate the clash of legitimacy for IDR between relevance and perceived quality (Hessels, 2010) since IDR is often funded on the premise of its social relevance, yet on the other hand, it is assessed in terms of citations.

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