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Are top-cited papers more interdisciplinary?

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ABSTRACT

Over the last decade, the relationship between interdisciplinarity and scientific impact has been the focus of many bibliometric papers, with diverging results. This paper aims at contributing to this body of research, by analyzing the level of interdisciplinarity, compiled with the Simpson Index, of the top 1% most highly cited papers and of papers with lower citation percentile ranks. Results shows that the top 1% most cited papers exhibit higher levels of interdisciplinarity than papers in other citation rank classes and that this relationship is observed in more than 90% of NSF specialties. This suggests that interdisciplinary research plays a more important role in generating high impact knowledge.

1. Introduction

It is now widely recognized that interdisciplinary research (IDR) is an effective model for stimulating innovation, sparking creativity and tackling pressing and complex societal issues (Aboelela et al., 2007, p. 330; Rafols, Leydesdorff, O'Hare, Nightingale, & Stirling, 2012, p. 1262; Rinia, 2007, pp. 5–6). Being usually problem- or mission-oriented in nature (Gibbons et al., 1994, p. 5; Hirsch Hadorn, Pohl, & Bammer, 2012; Klein, 1990, p. 58; Kueffer et al., 2012) it is claimed that IDR is especially apt to address large scientific challenges that require holistic integrative approaches from a variety of disciplines (Morillo, Bordons, & Gómez, 2003, p. 1237; NSF, 2009). IDR integrates heterogeneous knowledge to generate new one, which in turn can be diffused across several disciplines (Klein, 1990, p. 11; Liu, Rafols, & Rousseau, 2012; Meadows, 1976). Knowledge *integration* among two or more disciplines seems to be the fundamental element in the most widely accepted operational definitions of interdisciplinary research (Klein & Newell, 1998; National Academies, 2004; Porter, Roessner, Cohenm, & Perreault, 2006, p. 189; Porter & Rafols, 2009, p. 720), although slightly softer definitions of IDR (NSERC, 2012) will evoke *interaction* rather than *integration* among disciplines that *may* lead to "full integration of concepts, methodology, procedures, theory, terminology, data, organization of research and training."

Many important scientific discoveries and breakthroughs are obtained through interdisciplinary collaboration (Cummings & Kiesler, 2014). Striking instances of large-scale fruitful IDR endeavours that are often cited as exemplary research include for instance the discovery of DNA and the identification of its double-helix structure which was made possible through collaborative research among biologists, physicists and chemists, and the Human Genome Project which

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involved scientists from many disciplines, such as biology, chemistry, genetics, physics, mathematics, and computer science (Bretscher, 2008; Institute of Medicine, 2000, p. 24; Meldrum, 1995; Olby, 1974). These large-scale undertakings are indeed spectacularly successful but nowadays IDR is more and more prevalent even in small-scale projects that address problems that are inherently interdisciplinary. Consequently IDR is gaining recognition as an efficient *modus operandi* that many claim should be globally encouraged and aptly funded.

Over the last twenty years, much has been written about the pros and cons of IDR and whether or not it should be promoted in science policy. Interest in IDR emerged in the late 1960s and gained momentum after the 1970 seminar in Nice, organized under the auspices of the Organization for Economic Co-operation and Development (OECD) (Apostel, Berger, Michaud, & CERI, 1972; Weingart, 2012, p. 12). In a simple but persuasive study, Braun and Schubert (2003) provide quantitative evidence of the exponential growth of the use of the terms 'interdisciplinarity' and 'multidisciplinarity' in the scientific literature, especially since the 1990s, a testimony to the increasing interest in that topic.

Another significant work that stirred the debate and stimulated interest in IDR is the 1994 seminal report by Gibbons et al. (1994, p. 3) in which the authors assert the existence and emergence of a new mode of knowledge production "organised around [. . .] particular application[s]" that is gradually replacing the established discipline-based mode. This thesis has been met with skepticism by some (Jacobs & Frickel, 2009; Rhoten, 2004; Weingart, 1997) on the basis that it "has been based on impressionistic evidence only, [which] has not been supported by theoretical considerations or by systematic empirical evidence" (Weingart, 2012, p. 12) and that "many initiatives deemed interdisciplinary are, in fact, merely reconfigurations of old studies" (Rhoten, 2004, p. 6). Nonetheless, be it a trend or a full-fledged transition, many indicators, internal and external, corroborate the idea that a shift, moving from "traditional" discipline-based research, toward an interdisciplinary mode of production, has now been initiated. These indicators include for instance,

- the changing relations between and among disciplines and the emergence of many subdisciplines (specialties), along with the increase, since the mid-1980s, in interdisciplinary citations in scientific papers (van Leeuwen & Tijssen, 2000; Larivière & Gingras, 2014);
- the emergence of numerous cross- or interdisciplinary research centers (Siedlok & Hibbert, 2014), the creation of various interdisciplinary training and academic programs (Aboelela et al., 2007; Hackett & Rhoten, 2009; Mack, 2012, p. 3; NSB, 2014, pp. 2-29–2-30; NSF, 2009), and the formation of many interdisciplinary research teams (Boni, Weingart, & Evenson, 2009; Lungeanu, Huang, & Contractor, 2014);
- the founding of numerous new scholarly associations and journals who claim or encourage interdisciplinarity as part of their mission (Jacobs & Henderson, 2012), and the emergence of object-oriented research communities through informal communication networks (Sonnenwald, 2007);
- the recognition of the importance of IDR in research governance and science policy (Cooper, 2013; Lyall & Fletcher, 2013);
- the promotion of IDR by funding agencies (Bordons, Zulueta, Romero, & Barrigón, 1999; Lyall, Bruce, Marsden, & Meagher, 2013; Lyall & Meagher, 2012, p. 610; Rhoten & Pfirman, 2007; Sá, 2008); for example, Zhang, Hao, and Yan (2001, p. 64) showed that, over the course of the 20th century, the proportion of awarded Nobel prizes that are interdisciplinary in nature has risen from 36% to nearly 50%, with a marked increase during the last quarter of the century, which can be seen as a testimony to the "interconnected nature of modern cutting-edge science [. . . and] that the most interesting and ground-breaking work is done when scientists apply their talents in new fields" (Chemistry World, 2014).

Although these indicators show that there is undeniably a growing interest in IDR, not all agree that the current movement to promote and encourage IDR is worth the effort: "the case has [not] been fully made, theoretically or empirically, for the general superiority of interdisciplinarity over disciplinary knowledge" (Jacobs & Frickel, 2009, p. 60). Furthermore, many active researchers in the bibliometric community assert that "the literature [. . .] has not reached a point that permits meaningful assessment of IDR" (National Science Board, 2010, p. 5–35) and that "developing a generally agreed-on concept of interdisciplinary research and measuring how it has grown have proven to be challenging" (NSB, 2014, p. 5–18). Jacobs and Frickel (2009, p. 52) remain critical and assert that: "systematic efforts to develop evaluative criteria for judging interdisciplinary knowledge have been slow to develop, and direct empirical evidence on how the quality of interdisciplinary research is assessed remains thin." Despite these critics, there is much agreement that there is a need for more empirical data on the worth and validity of IDR. In order to contribute to this ongoing debate, this paper assesses the interdisciplinarity level of papers, and its relationship with the scientific impact of scientific papers, as measured by percentile rank in the citation distribution.

2. Literature review

Empirical research on the measurement and evaluation of IDR is indeed slow to materialize, but throughout the past decade or so the bibliometric community has been increasingly focusing on that problem and IDR has emerged as an important topic in the scientific literature.

2.1. Interdisciplinarity evolution and variation

Various indicators have been proposed to measure IDR activity. Such indicators, typically compiled using bibliometric methods, have mainly relied on the discipline and specialty of cited documents, which allowed to compile "the percentage of citations within and outside of the disciplinary groupings" (McCain & Whitney, 1994, p. 286). Porter and Chubin (1985) showed that Citation Outside Category can be used as a valid indicator of IDR activity. In their analysis they found that citations outside broad categories are infrequent. In a small-scale study, Hurd (1992) looked at publication patterns of faculty at a chemistry university department and measured a relatively high degree of interdisciplinarity (over 49%) in their published scientific literature, although, in her analysis she conjectures that "detailed analysis of interdisciplinarity variation by specialty [. . .] might reveal significant differences in use of materials" (p. 294). This was to be confirmed by subsequent studies, notably that of Qin, Lancaster, and Allen (1997) who studied the literature from the natural sciences and found that "the levels and types of interdisciplinarity collaboration varied in different disciplines" (p. 914). Another small-scale study by Ortega and Antell (2006) also showed that, while cross-disciplinary citation rates in Chemistry increased from 1985 to 2000, it was not the case for Biology and Physics. The heterogeneity of interdisciplinarity pattern amongst disciplines was also detected by van Leeuwen and Tijssen (2000) who, despite observing – through analysis of cross disciplinary citations – an "increase in interdisciplinarity across a wide variety of disciplines," note that there are "significant differences between [*sic*] disciplines in terms of interdisciplinary orientation" (p. 187).

Porter and Rafols (2009) studied six domains in the natural sciences over a 30-year period and measured increased interdisciplinarity in all six domains which led them to conclude that "science is [. . .] becoming more interdisciplinary but in small steps" (p. 741). Also, in their longitudinal study, Gingras and Larivière (2010) found that "the historical patterns [of interdisciplinarity] differ greatly whether we look at natural, social or biomedical sciences [but that] in all cases though, interdisciplinarity raises since the 1990s" (p. 100). Levitt, Thelwall, and Oppenheim (2011) who studied 14 social sciences subjects arrive at a similar conclusion: "interdisciplinarity in social science [. . .] increased substantially between 1990 and 2000 [but it] varied considerably between [*sic*] subjects" (p. 1127). On the whole, most bibliometric studies tend to indicate that IDR is on the rise, especially since the 1990s, but that the progression is occurring at various rates among disciplines.

2.2. Impact of IDR

Another issue that is frequently addressed in the literature relates to the scientific impact of IDR. Many researchers claim that IDR plays a critical role in science and produces many ground-breaking scientific discovery. Several studies try to provide empirical evidence on the importance of IDR in science by comparing quantitative measures – usually based on scientific impact – between disciplinary and interdisciplinary research.

Since citation count is commonly considered to be closely correlated with scientific impact, several studies have explored the citation rates difference between interdisciplinary and disciplinary research and many of these find a positive relation indicating that IDR generates higher scientific impact over disciplinary research. Levitt and Thelwall (2009) investigated the citation counts of highly cited papers in the field of Information Science and Library Science. They found that, in general, papers published in multidisciplinary journals (i.e., papers published in journals covering IS&LS as well as at least one other discipline) have a much higher incidence in their sample of highly cited papers than papers published in strictly disciplinary journals. The results of their study thus suggest that promotion of IDR "in IS&LS may be conducive to improving its quality of research" (p. 57). Using Brillouin's diversity index, Steele and Stier (2000) studied the forestry scientific literature to measure articles' interdisciplinarity from the perspective of their authors, subject matter and cited literature. They found a positive correlation between the degree of interdisciplinarity of articles and their citation frequency which indicates that "interdisciplinary methods have made a measurable and positive impact on the forestry literature" (p. 476).

Results from other studies show a negative relation and indicate that IDR does not necessarily produce higher impact papers than does disciplinary research. In their study of physics research programs in the Netherlands, Rinia, van Leeuwen, and van Raan (2002) showed that interdisciplinary programs have received lower scores on "a number of 'elementary' bibliometric indicators" (p. 245) such as absolute number of citations and impact factors of journals in which they publish, which suggests that interdisciplinary research is disadvantaged by traditional bibliometric indicators. Using the interdisciplinarity of cited references among the Thomson Current Contents subject categories and discipline-normalized citation counts of two research-intensive United Kingdom universities, Adams, Jackson, and Marshall (2007) found that the most interdisciplinary articles were in fact cited as much as the average article. They also found that the cited references of the most cited articles had average levels of interdisciplinarity – rather than very low or very high levels of interdisciplinarity – and conclude that "there is no evidence to support [the claim that interdisciplinary] articles receive systematically fewer citations than more monodisciplinary publications" (p. 2). Levitt and Thelwall (2008) conducted a macrolevel study on the scientific impact of IDR in a variety of subjects in order to measure "the extent to which the level of disciplinarity correlates with citation" (p. 1973). Their results indicate that in the natural and health sciences, IDR – defined as papers published in journals to which more than one subject category was assigned – has a weaker scientific impact than disciplinary research and that in the social sciences, both types of research obtain similar citation rates.

Along these lines, Larivière and Gingras (2010) obtained mixed results as they could not measure a clear direct correlation between the level of interdisciplinarity of articles and their citation rates. At a finer level of analysis, they showed that for some disciplines "a higher degree of interdisciplinarity is correlated with lower citation rates [whereas in other disciplines] a moderate interdisciplinarity is associated with higher citation rates" (p. 129). More recently, Larivière, Haustein, and Börner (2015) compiled the citations received of over nine million interdisciplinary articles, based on the interdisciplinarity of the references they cite. Their analysis show that the majority (nearly 70%) of co-cited interdisciplinary pairs form a "win-win" relationship (i.e., papers that cite them have higher citation impact) whereas only a small proportion (3.3%) form a "lose-lose" relationship. They also showed that distance between subdisciplines of co-cited papers – obtained using their position on the UCSD map (Börner et al., 2012) – was positively associated with scientific impact. In other words, the more distant on the UCSD map the co-cited subdisciplines pairs were, the higher the scientific impact. Also working at the level of pairs of cited papers, Uzzi, Mukherjee, Stringer, and Jones (2013) showed that papers citing both *atypical* and *conventional* pairs of papers were the most cited. Such results, however, vary across disciplines (Boyack & Klavans, 2014). Using three aspects of interdisciplinary relationships – variety, balance, and disparity – Wang, Thijs, and Glänzel (2015) show that the effect of interdisciplinarity on impact varies with the indicator and citation window used: while variety and disparity have a positive effect on long-term citations, balance is associated with a decrease in citations. However, positive effects for variety and disparity are not observed on the short term and the effects are significantly negative in the short term for variety and disparity. Their approach was similar to the one previously used by Yegros, D'Este, and Rafols (2013) who found an inverted U-shaped relationship between degree of interdisciplinarity and citation impact.

On the whole, previous studies on the relationship between interdisciplinarity and scientific impact obtained diverging results, mainly because of the different IDR indicators used as well as of the different disciplines on which they focused. There is, however, one finding that is common to most bibliometric studies performed thus far: when conceptualized and operationalized using cited references, strictly disciplinary research typically receives a lower number of citations.

A recent study by Chen, Arsenault, Gingras, and Larivière (2015)(November 2014) analyzed highly cited papers to compare the performance of IDR over disciplinary research over a one hundred year period. The study findings reveal the importance of IDR, more specifically at the specialty level, "as it provides most of the references of these highly cited papers" (p. 2). Based on these results we can conjecture that there might be a correlation between a paper's percentile rank in terms of citations received and its level of interdisciplinarity. That is to say, do high top cited papers exhibit high levels of interdisciplinary? In this paper we propose to explore the phenomena of interdisciplinarity from the angle of percentile rank class, in order to assess whether top cited papers are more likely to be interdisciplinary, and to measure the extent to which a higher level of interdisciplinarity leads to a higher percentile rank in the distribution of citations.

3. Data and methods

3.1. Data Set

Our data set is composed of all journal articles (source items) indexed in Thomson Reuters' Web of Science published in the year 2000 (totaling 751,766 source items in various disciplines) and the list of references they cited which could be found in the database as a source item. Citations are counted until the end of 2013. Hence, scientific impact measured here can be considered as long term (Wang et al., 2015). The year 2000 was chosen for two reasons: first, it allows enough time to measure the scientific impact of the papers; second, it reuses the same data set from the Larivière and Gingras (2010) study which makes it easier to compare results.

3.2. Discipline classification and definitions

The disciplinary classification of journals used in this study is that of the U.S. National Science Foundation (NSF) which categorizes each journal into one and only one discipline and specialty (i.e., subdiscipline). This classification includes 14 general disciplines that are declined into 143 specialties. Our study explores interdisciplinarity from the perspective of both disciplines and specialties (i. e., interspecialty) which roughly corresponds to Rinia's two levels of interdisciplinarity, "big" and "small" (Rinia, 2007). We adapt this framework to the NSF classification system and analyze interdisciplinarity from the perspective of "interdisciplinarity" (big interdisciplinarity) and "interspecialty" (small interdisciplinarity), respectively.

3.3. Percentiles and percentile rank classes

Our methodology uses percentiles and percentile rank classes (PR) which, given the skewness of citation distributions (Seglen, 1992), are seen as an alternative to mean-based indicators for obtaining a normalized citation impact of publications (Bornmann, Leydesdorff, & Mutz, 2013a, p. 164). A percentile is simply defined as "a value below which a certain proportion of the observations fall" (Bornmann et al., 2013a, p. 159). Each source item from our data set was assigned to a percentile in terms of its position in the citation distribution of papers from the same specialty in the dataset. In this paper we follow the procedure presented in Bornmann et al. (2013b, p. 935) to compute the percentile rank of each source item. The procedure follows three basic steps:

(1) All source items in the set were ranked in decreasing order by their number of citations over the 2000–2013 period; publications with equal citation counts were assigned their average rank;

(2) The percentile rank of each publication was computed using the formula $100 \times (i - 0.5)/n$ (n being the number of papers and i the rank value) (see Bornmann et al., 2013a, p. 159–160, for more details on this);
(3) Publications with zero citations were assigned a rank of 0.

In order to interpret the performance of a publication unambiguously, each publication can be assigned to a PR. The most commonly used PR schemes are those that calculate the proportion of frequently (the top x%) cited publications (Waltman & Schreiber, 2013). The value of x is often set to 10 (Bornmann, de Moya Anegón, & Leydesdorff, 2012; Waltman et al., 2012) since the top 10% is usually used to evaluate the research performance of scientists, research institutes, research groups, countries or other units. Another commonly used scheme, referred to as PR(6), divides publications into six percentile rank classes. PR(6) is the scheme applied by the US National Science Foundation (NSF) in their Science and Engineering Indicators (NSB, 2014, p. 5-48–5-62) and by Thomson Reuters in their Essential Science Indicators (ESI).[1]

In our study we use the six percentile classes of the NSF which are as follows:

(1) $PR_{<50th}$ (papers with a percentile smaller than the 50th percentile),
(2) PR_{50th} (papers within the 50th and 75th percentile interval),
(3) PR_{75th} (papers within the 75th and 90th percentile interval),
(4) PR_{90th} (papers within the 90th and 95th percentile interval),
(5) PR_{95th} (papers within the 95th and 99th percentile interval),
(6) PR_{99th} (papers with a percentile equal to or larger than the 99th percentile).

3.4. Interdisciplinary distribution indicator

In a recent report, Wang et al. (2015) indicate that "one possible explanation for [. . .] conflicting results pertains to [. . .] different choices of the interdisciplinarity measure." Furthermore, they remind us that interdisciplinarity is a concept that can be operationalized in several manners—all of which can lead to different types of indicators which, in turn, measure different dimensions of the concept. Yegros et al. (2013) surveyed the variety of indicators developed to measure IDR and illustrated how these indicators taken individually fail to provide a comprehensive measure that would incorporate all the attributes of diversity identified by Stirling (2007, p. 709), namely variety, balance and disparity/similarity. The latter of these three attributes refers to "the manner and degree in which the elements may be distinguished" and cannot be measured by typical diversity measures such as Simpson's (Rafols & Meyer, 2010) upon which our indicator is based. As a consequence, our results can only provide insights variety (number of disciplines cited) and balance (proportions of references in each discipline) dimensions of the indicator.

The reverse Simpson index is adopted in this paper because it is simple to calculate and it is a normalized indicator (namely its values range from 0 to 1). The Simpson index (λ) is "a measure of the concentration of the classification" when individuals are classified into groups (R). More specifically, λ refers to "the probability that two individuals chosen at random and independently from the population will be found to belong to the same group" (Simpson, 1949, 688):

$$\lambda = \sum_{i=1}^{R} p_i^2$$

With this definition and formula, λ would attain small values in datasets of high diversity (in our case high interdisciplinarity) and large values in datasets of low diversity (in our case low interdisciplinarity) which is somewhat counterintuitive for an interdisciplinarity indicator. Taking this into account we have instead used the transformed Simpson index $(1 - \lambda)$ to reverse the indicator so that its values increase rather than decrease with interdisciplinarity which is the property we aimed to measure.

Fig. 1a and b, respectively, present the distribution of publications as a function of their interspecialty and interdisciplinarity scores based on the Simpson index. Values ranging from 0 up to 0.1 are compiled as 0.1, those above 0.1 up to 0.2 as 0.2, and so on. As can be seen on the figures the distribution of interspecialty and interdisciplinarity is not distributed evenly. For interspecialty, publications fall mainly in Simpson index values of 0.1, and between 0.4 and 0.8. For interdisciplinarity, more than half of publications are concentrated in Simpson values between of 0 and 0.1 and between 0.4 and 0.5. Furthermore we observe that very few publications have high levels of interdisciplinarity. On the whole, both figures exhibit distributions that are skewed.

In order to take into account the skewness of the distributions, we used a rank-based interdisciplinarity indicator, namely the Simpson Expected Value (SEV). SEV is similar to the Discipline Interdisciplinary Indicator (DII) defined in our previous study (Chen, Arsenault, Gingras, & Larivière, 2015). SEV is more suitable for describing the interdisciplinarity characteristics of percentile rank classes as it is constructed on the basis of percentile rank scores (PRS), used to describe the citation counts distribution in evaluative scientometrics (Bornmann, 2010, p. 441). In our study we divided articles into ten interdisciplinarity

[1] The six percentile rank classes used in ESI are slightly different than those of the NSF. The citation count thresholds on six percentile rank class (namely top 50%, top 20%, top 10%, top 1%, top 0.1% and top 0.01%) are defined in the baselines of ESI: http://esi.webofknowledge.com/help/h_datbas.htm.

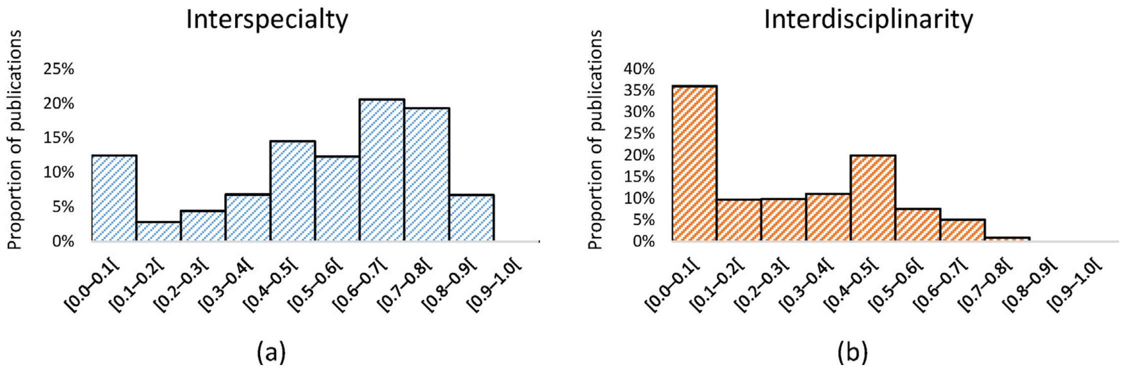

Fig. 1. Distribution of publications as a function of their interspecialty (a) and interdisciplinarity (b).

rank classes according to their Simpson index, ranging from 0.0–0.1, to 0.9–1.0. SEV is calculated using the following formula:

$$\mathrm{SEV} = \sum_{x=1}^{K} x \cdot p(x)$$

K denotes the number of interdisciplinarity rank classes, x is a discrete variable with $x = 1$ to K, and $p(x)$ its percentage of articles in a given interdisciplinary rank class. An example of how SEV is calculated is presented in Appendix A. The probability that an article falls in a given interdisciplinarity rank class is proportional to the width of the rank class. Given that SEV classes all have the same width ([0.0–0.1[, [0.1–0.2[... [0.9–1.0[), and that there are 10 SEV classes, the probability that an article falls in a given SEV class is 0.1. This expected SEV is taken as the reference SEV and obtained by summing up the products of interdisciplinarity rank class proportions with the class number, according to the following calculation: $0.1 \times (1+2+3+4+5+6+7+8+9+10) = 5.5$. Papers with SEV values above 5.5 are therefore considered as more interdisciplinary than expected.

3.5. Interdisciplinarity change score

Our study explores the relation between interdisciplinarity distribution characteristics and percentile rank classes at the level of NSF disciplines and specialties, respectively. There are only fourteen disciplines in the NSF classification systems, so at the discipline level, it is easy to visually analyze the interdisciplinary distributions on simple histograms. However, at the specialty level, the task of analyzing the correlation between interdisciplinarity and percentile rank class becomes cumbersome because of the high number of specialties (143 in the NSF classification), and representation through histograms is not conducive to visual analysis. We therefore defined an Interdisciplinarity Change Score (ICS) to determine the correlation between interdisciplinarity and percentile rank class at the specialty level. To compute the ICS index for specialties, we arranged our original six percentile rank classes in order from $\mathrm{PR}_{99\mathrm{th}}$ to $\mathrm{PR}_{<50\mathrm{th}}$, computed SEV of each percentile rank class and obtained the ICS score by comparing interdisciplinarity of one percentile rank class with that of the neighboring percentile rank classes. The formula used to calculate the ICS is as follows (where N is the number of percentile rank classes (in this study six)[2]):

$$\mathrm{ICS} = \sum_{i=1}^{N-1} \delta\left(\mathrm{SEV}_{\mathrm{PR}_i}, \mathrm{SEV}_{\mathrm{PR}_{i+1}}\right)$$

$\mathrm{SEV}_{\mathrm{PR}_i}$ is the ICS score of the PR_i percentile rank class. If $\mathrm{SEVPR}_i > \mathrm{SEV}_{\mathrm{PR}_{i+1}}$, then $\delta\left(\mathrm{SEVPR}_i, \mathrm{SEV}_{\mathrm{PR}_{i+1}}\right) = 1$, otherwise $\delta\left(\mathrm{SEVPR}_i, \mathrm{SEV}_{\mathrm{PR}_{i+1}}\right) = 0$. With this calculation, when within one specialty the SEV value at any given percentile rank class is consistently higher than the value measured in the preceding percentile rank class, the ICS of that specialty equates 5. On that basis, with a six-level scheme, ICS scores can range from 0 to 5. To further analyze specialties whose ICS score is lower than 5 we calculate a second ICS, this time based on a three-level rank class obtained by aggregating the six percentile rank classes into a three-level scheme, namely "high", "medium" and "low" percentile ranks. The "high" percentile rank combines $\mathrm{PR}_{99\mathrm{th}}$, $\mathrm{PR}_{95\mathrm{th}}$ and $\mathrm{PR}_{90\mathrm{th}}$, the "medium" percentile rank includes $\mathrm{PR}_{75\mathrm{th}}$ and $\mathrm{PR}_{50\mathrm{th}}$, whereas the low percentile rank is equal to $\mathrm{PR}_{<50\mathrm{th}}$. When a specialty's original ICS score was lower than 5, we computed a new ICS according to the three-level aggregated scheme. Because this scheme has three levels, the ICS scores can range from 0 to 2 and we believe that a new

[2] The six percentile rank classes, namely $\mathrm{PR}_{99\mathrm{th}}$, $\mathrm{PR}_{95\mathrm{th}}$, $\mathrm{PR}_{90\mathrm{th}}$, $\mathrm{PR}_{75\mathrm{th}}$, $\mathrm{PR}_{50\mathrm{th}}$, $\mathrm{PR}_{<50\mathrm{th}}$, are defined from 1 to 6 and renamed as PR_1, PR_2, PR_3, PR_4, PR_5, PR_6.

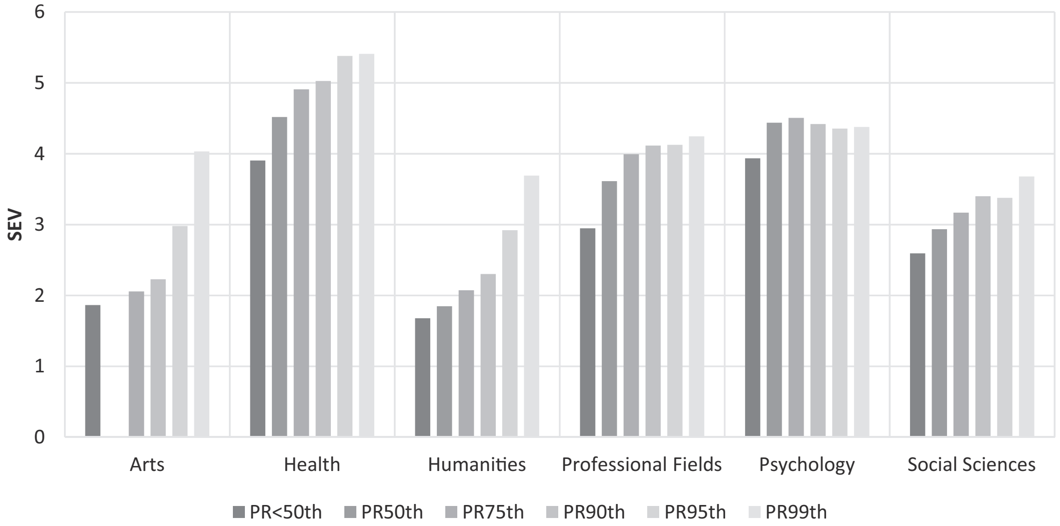

Fig. 2. Interdisciplinarity (SEV) as a function of papers' citation percentile rank class—Social Sciences and Humanities.

ICS score of 2 would be indicative of a fairly high level of interdisciplinarity in higher percentile rank classes. In order to distinguish our two ICS scores, "ICS_{6}" is used to designate the ICS based on the six-level percentile rank class scheme, and "ICS_{3}" is used to designate the ICS based on the aggregated three-level percentile rank class scheme.

4. Results

4.1. Interdisciplinarity and scientific impact at the level of disciplines

Fig. 2, for Social Sciences and Humanities, and Fig. 3, for Natural Sciences and Medicine, present for each discipline, the SEV of a group of papers as a function of their percentile rank score in terms of citations. Most of the histograms presented in the two figures show that groups of papers with a higher percentile rank class in terms of citations also exhibit higher levels of interdisciplinarity (SEV). For Social Sciences and Humanities disciplines, only Psychology exhibits a somewhat different pattern than the other disciplines as its median percentile rank classes have slightly higher interdisciplinarity than the high and the low percentile rank classes. For disciplines in Natural Sciences and Medicine, only two of the eight disciplines, namely Biomedical Research and Earth and Space, have interdisciplinarity patterns that are not increasing regularly along with the percentile rank classes. The interdisciplinarity of Biomedical Research decreases all through the increasing percentile rank

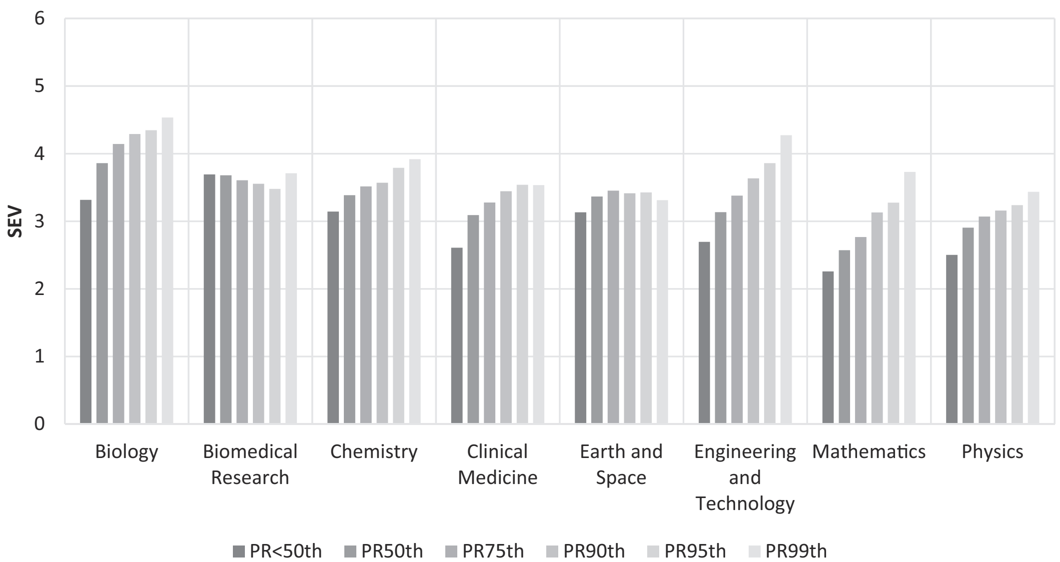

Fig. 3. Interdisciplinarity (SEV) as a function of papers' citation percentile rank class—Natural Science and Medicine.

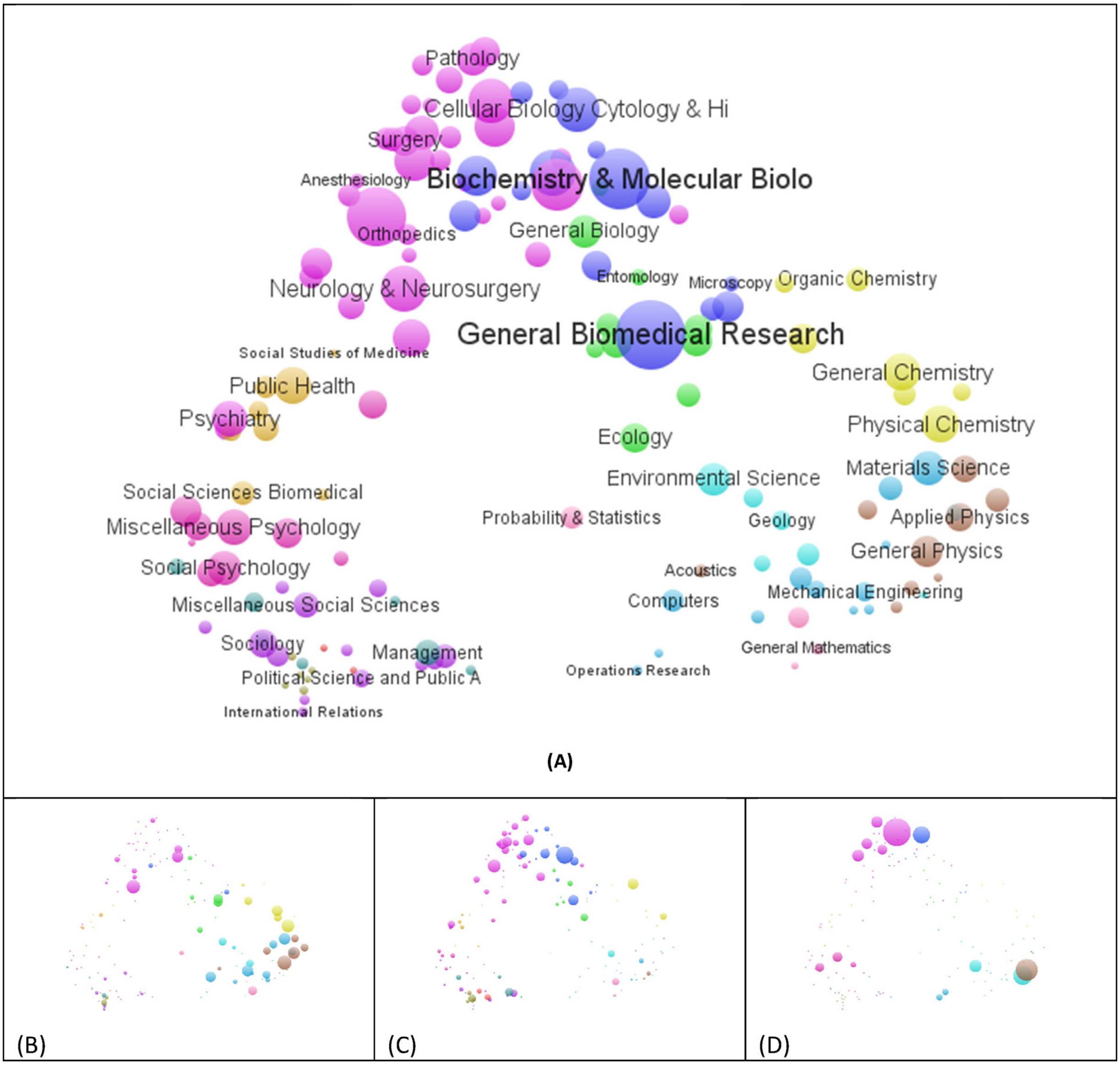

Fig. 4. Science map of NSF disciplines. (A) All relationships; (B) Type-1 specialties; (C) Type-2 specialties; (D) Type-3 specialties.

classes, up until the PR_{99th} where it raises sharply; for Earth and Space we observe a similar pattern that was observed with Psychology: its median percentile rank classes show more interdisciplinarity than the lower and higher rank classes.

The results globally show that, for most disciplines, the higher the percentile rank, the more important the interdisciplinary research. As it is shown on the histograms, interdisciplinary research is usually more important for high percentile rank than low percentile rank classes. This is a very interesting phenomenon. Whether IDR plays an important role in one discipline or not, our data clearly shows that IDR is more important for high percentile rank than for low percentile rank.

4.2. Interdisciplinarity and scientific impact at the level of specialties

By examining the SEV values obtained for the 143 NSF specialties through our six citation percentile rank classes, we find that 65 specialties (45.5%) obtain values above 5.5 in all six percentile rank classes. In addition, the SEV value is above 5.5 for 117 specialties (81.8%) at PR_{99th}, for 108 specialties (75.5%) at PR_{99th} and PR_{95th}, and for 103 specialties (72%) at PR_{99th}, PR_{95th} and PR_{90th} (see Table 1). As it can be considered that papers in PR_{99th}, PR_{95th} and PR_{90th} represent highly cited papers and that high citation is often associated with high research quality, we can infer that, for most specialties, interdisciplinary research (at the interspecialty level) has a greater scientific impact.

Table 1
Number (proportion) of specialties with SEV values above 5.5.

Percentile rank class	Number of specialties with SEV above 5.5
PR_{99th}	117 (81.8%)
PR_{99th} and PR_{95th}	108 (75.5%)
PR_{99th}, PR_{95th} and PR_{90th}	103 (72.0%)
All PRs	065 (45.5%)

Table 2
Number (proportion) of specialties by type.

Specialty type	Number of specialties
Type-1 specialties ($ICS_6 = 5$)	52 (36.4%)
Type-2 specialties ($ICS_6 < 5$ and $ICS_3 = 2$)	77 (53.8%)
Type-3 specialties ($ICS_6 < 5$ and $ICS_3 < 2$)	14 (09.8%)

The relationship between interspecialty and the percentile rank classes is examined further by computing the ICS of the 143 specialties for the six percentile rank classes and for the aggregated three-level percentile rank classes ("high," "medium" and "low" as defined above in the methods section). Based on the ICS scores obtained we can divide the specialties into three types. Type-1 specialties are those with an ICS_6 score of 5. These specialties see their interdisciplinarity increase steadily with the increase of each percentile rank class. Type-2 specialties are those whose ICS_6 score is lower than 5 but with an ICS_3 score of 2 (i.e., their interdisciplinarity also increases with the increase of each aggregated percentile rank class, but to a lesser degree). Type-3 specialties are those where no obvious relationship between interdisciplinarity and percentile rank classes was observed. Results are summarized in Table 2.

We used science overlay maps (Fig. 4A–D) based on the NSF classification system to visualize the specialties by type. We identified 52 specialties (36.4%) of type-1 whose ICS_6 is equal to 5. Fig. 3b presents these specialties' distribution on the global NSF science map. We can clearly see that most of these specialties occupy the bottom right of the map. We also find some specialties located at the upper end of the map but only a few specialties located at bottom left of the map. These specialties mostly belong to the fields of Engineering and Technology, Clinical Medicine, Physics, Chemistry, and Social Sciences. We found 77 specialties (53.8%) in the type-2 category because, although their ICS_6 is lower than 5, their ICS_3 is equal to 2. These specialties appear on Fig. 3c. It was interesting to note that most type-2 specialties are located at the upper part of the science overlay map, the zone which mainly includes Biomedical Research, Clinical Medicine, and Biology; the bottom left of the map is also populated with type-2 specialties including Social Sciences, Psychology, Health, Humanities. Finally, type-3 specialties (whose ICS_6 is lower than 5 and ICS_3 is lower than 2) include 14 specialties (9.8%) illustrated on Fig. 3d. Quite evidently we note that these specialties tend to distribute at the three poles of the map, areas far away from interaction between disciplines. On the whole, these figures suggest that specialties that benefit most, in terms of citations, from citing other specialties are those that have higher interdisciplinary ties, while disciplines that are more insular do not benefit, in terms of citations, from such interdisciplinary relationships.

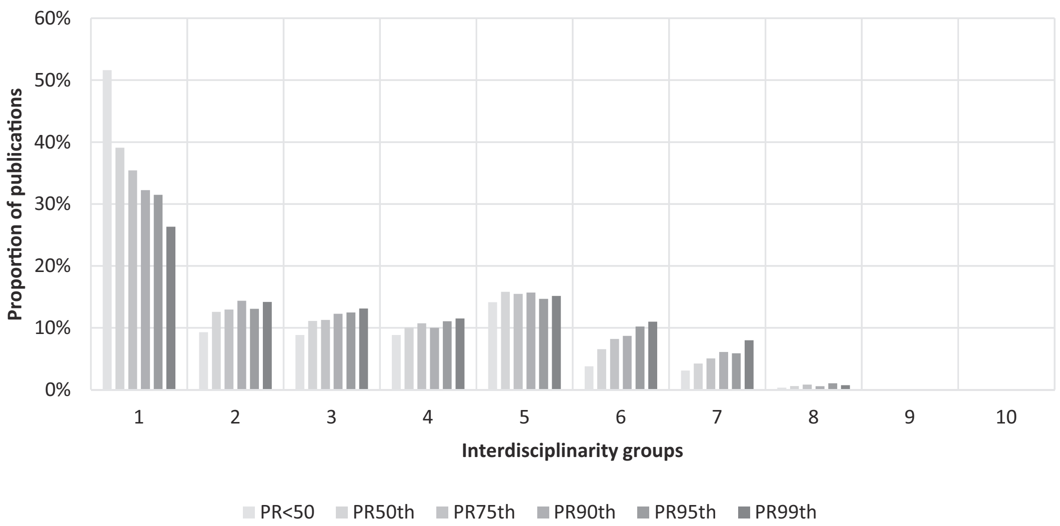

Fig. 5. Proportion of publications of the six citation percentile ranks, as a function of its interdisciplinarity group (Physics).

4.3. Interdisciplinarity classes and scientific impact: A closer look at physics

In order to test this phenomenon further, we analyzed the interdisciplinarity characteristics of Physics papers. Physics papers, totaling 90,874 source items published in the year 2000, were divided into ten groups on the basis of their interdisciplinarity value; interdisciplinarity between 0 and 0.1 are compiled in group 1, those between 0.1 and 0.2 in group 2, and so on, for a total of 10 classes (Fig. 5). It shows that in group 1 (papers that are essentially mono-disciplinary), there is a greater proportion of papers in the lower citation rank-classes, and a lesser proportion in the high percentile ranks. In the other interdisciplinary groups (except in group 5 where no clear pattern can be detected), a greater proportion of publications can be found in high percentile ranks than in low percentile ranks. These results confirm, for the field of physics, the positive relationship between papers' level of interdisciplinarity and their scientific impact.

5. Discussion and conclusion

Over the last decade or so, the relationship between interdisciplinarity and scientific impact has been the focus of many bibliometric papers, using different methods and obtaining, often, diverging results. For instance, while Adams et al. (2007), Larivière and Gingras (2010), Larivière et al. (2015), Uzzi et al. (2013) and Wang et al. (2015) all operationalize interdisciplinarity through the analysis of papers' cited references, they do not completely agree on the extent to which interdisciplinarity affect scientific impact. This paper aims a contributing to this debate, by analyzing the level of interdisciplinarity, using the Simpson Index, of top 1% most highly cited papers, as well as of papers of lower citation percentile ranks. It shows that, in each and every discipline – except Earth and Space –, the top 1% most cited papers exhibit higher levels of interdisciplinarity than papers in other citation rank classes. At the level of NSF specialties, in the large majority of cases (90.2%) interdisciplinarity increase steadily with the increase of citation percentile rank class.

Previous research Chen et al. (2014), validated the importance of IDR as it showed that, over the past 30 years or so interdisciplinary papers provide most of the references to a set of highly cited papers (the top 1%), especially when we consider interspecialty (i.e., relationships between subfields). Since highly cited papers can be considered as high quality papers that play a critical role in the development of science, it is possible to conjecture that IDR plays a more critical role than disciplinary research in creating major discoveries or that its scientific impact is greater. The present study reinforced that idea since, for most disciplines and specialties, the interdisciplinarity in the high percentile rank class is higher than that in the low percentile rank classes. From these results we can then infer that IDR plays a more important role in the high percentile rank classes of citations than in the low percentile rank classes. It is essential to note that since our measures are obtained through percentile rank classes for a set of publications, we cannot conclude that, for a single article, being more interdisciplinary will inherently result in higher scientific impact.

In a manner similar to Larivière and Gingras (2010), our results also show that the increase of papers' citation rates as a function of interdisciplinarity is higher for subfields with lower citation rates (Humanities, Mathematics, Engineering and Technology, etc.) than for subfields with higher citation rates, like Biomedical Research. Indeed, for the latter field, we observe a decrease in the level of interdisciplinarity of papers as heir citation rank increases – except for the top 1% most cited papers, which have the highest level of interdisciplinarity. This suggests that, by citing papers from other disciplines and specialties – which is the basis of the interdisciplinarity indicator used here – papers become more associated to the fields they cite rather than to the journal in which they are published and, hence, are more likely to obtain the citation rates of the fields they cite. For example, a paper that is published in a journal from the Humanities—where citation rates are low—that cites a lot of Biomedical Research—where citation rates are high – is more likely to be, in turn, cited by Biomedical Research papers and, hence, obtain citation rates that are greater than those of the typical Humanities paper[3]. In this context, the use of the citing side field-normalization method – where papers' citation rates are compared to those of papers having similar referencing behavior (Zitt & Small, 2008; Waltman & van Eck, 2013) – might provide different results. Bringing emphasis on the citation normalization method rather than on the operationalization of the concept of interdisciplinarity, would likely contribute to a better understanting of this complex and controversial relationship.

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Author contributions

Conceived and designed the analysis: Shiji Chen; Clément Arsenault; Vincent Larivière
Collected the data: Vincent Larivière

[3] Data presented in Table 1 in Larivière and Gingras (2010) seem to confirm this hypothesis.

Performed the analysis: Shiji Chen
Wrote the paper: Shiji Chen; Clément Arsenault; Vincent Larivière

Appendix A.

We take Physics as an example to illustrate the calculation process of disciplinary SEV. Our data contained 90,874 Physics papers. The number of papers and their proportion in each interdisciplinary rank class is listed in Table A1. Using our formula

Table A1
Number of publications, class number (x), and proportion ($p(x)$) of each class in Physics.

Interdisciplinary rank class*	x	Number of papers	$P(x)$
0.1	1	39,799	0.44
0.2	2	10,151	0.11
0.3	3	9,251	0.10
0.4	4	8,746	0.10
0.5	5	13,539	0.15
0.6	6	5,242	0.06
0.7	7	3,650	0.04
0.8	8	488	0.01
0.9	9	8	0.00
1	10	0	0.00

* In the column of interdisciplinary rank class, rank 0.1 indicates interdisciplinarity ranging from 0 up to 0.1, rank 0.2 indicates interdisciplinarity above 0.1 up to 0.2, and so on.

we can calculate the SEV of Physics as follows:

$$SEV_{physics} = 1 \times 0.44 + 2 \times 0.11 + 3 \times 0.10 + 4 \times 0.10 + 5 \times 0.15 + 6 \times 0.06 + 7 \times 0.04 + 8 \times 0.01 + 9 \times 0.00 + 10 \times 0.00 = 2.83$$

In the column of interdisciplinary rank class, rank 0.1 indicates interdisciplinarity ranging from 0 up to 0.1, rank 0.2 indicates interdisciplinarity above 0.1 up to 0.2, and so on.

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