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BIAS AGAINST NOVELTY IN SCIENCE:
A CAUTIONARY TALE FOR USERS OF BIBLIOMETRIC INDICATORS

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ABSTRACT

Research which explores uncharted waters has a high potential for major impact but also carries a higher uncertainty of having impact. Such explorative research is often described as taking a novel approach. This study examines the complex relationship between pursuing a novel approach and impact. Viewing scientific research as a combinatorial process, we measure novelty in science by examining whether a published paper makes first time ever combinations of referenced journals, taking into account the difficulty of making such combinations. We apply this newly developed measure of novelty to all Web of Science research articles published in 2001 across all scientific disciplines. We find that highly novel papers, defined to be those that make more (distant) new combinations, deliver high gains to science: they are more likely to be a top 1% highly cited paper in the long run, to inspire follow on highly cited research, and to be cited in a broader set of disciplines. At the same time, novel research is also more risky, reflected by a higher variance in its citation performance. In addition, we find that novel research is significantly more highly cited in “foreign” fields but not in its “home” field. We also find strong evidence of delayed recognition of novel papers and that novel papers are less likely to be top cited when using a short time window. Finally, novel papers typically are published in journals with a lower than expected Impact Factor. These findings suggest that science policy, in particular funding decisions which rely on traditional bibliometric indicators based on short-term direct citation counts and Journal Impact Factors, may be biased against “high risk/high gain” novel research. The findings also caution against a mono-disciplinary approach in peer review to assess the true value of novel research.

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1. Introduction

Scientific breakthroughs advance the knowledge frontier. Research underpinning breakthroughs often is driven by novel approaches. While research that takes a novel approach has a higher potential for major impact, it also faces a higher level of uncertainty of impact. In addition, it may take longer for novel research to have a major impact, either because of resistance from incumbent scientific paradigms (Kuhn, 1962; Merton, 1973; Planck, 1950) or because of the longer time required to incorporate the findings of novel research into follow-on research (Garfield, 1980; Wyatt, 1975). The “high risk/high gain” nature of novel research makes it particularly appropriate for public support (Arrow, 1962). Delayed recognition may, however, lead novel research to be undervalued in research evaluations which use classic bibliometric indicators based on short term citations.

This bias in classic bibliometric indicators against novel research, to the extent it exists, is of concern given the increased reliance funding agencies and hiring institutions place on bibliometric indicators to aid in decision making and performance evaluation (Butler, 2003; Hicks, 2012; Hicks, Wouters, Waltman, de Rijcke, & Rafols, 2015; Martin, 2016; Monastersky, 2005). Such heavy reliance may explain in part the perception that funding agencies and their expert panels are increasingly risk-averse and the charge that competitive selection procedures encourage relatively safe projects, which exploit existing knowledge, at the expense of novel projects, that explore untested approaches (Alberts, 2010; Azoulay, Graff Zivin, & Manso, 2011; Kolata, 2009; NPR, 2013; Petsko, 2012; Walsh, 2013).

The goal of this paper is to develop a measure of novel research and compare the citation profile of novel research with that of non-novel research as well as the Impact Factor of the journals in which novel research is published. We are particularly interested in whether characteristics of novel research match the “high risk/high gain” profile associated with breakthrough research and whether bibliometric measures are biased against novel research. To this end, we define research that draws on new combinations of knowledge components as novel and develop an *ex ante* measure of combinatorial novelty at the paper level, where novelty is operationalized as making new combinations in referenced journals. Utilizing this newly-minted measure of novelty, we explore the complex relationship between novelty and citation impact, using the life-time citation

trajectories of 773,311 research articles across all scientific disciplines published in 2001 and indexed in the Web of Science (WoS), as well as the profile of papers citing them.

We find novel papers to have a larger variance in their citation distribution and be more likely to populate both the tail of high impact as well as the tail of low impact, reflecting their “high risk” profile. At the same time, novel papers also display a “high gain” characteristic: They have a much higher chance of being a top cited paper in the long run, a higher likelihood of stimulating follow-on top cited research, and a broader impact transcending disciplinary boundaries and reaching more scientific fields. We further scrutinize the impact profile of novel research and uncover intriguing characteristics associated with novelty. First, we distinguish between impact in “home” and “foreign” fields and find that novel papers are significantly more likely to be highly cited in foreign fields but not in their home field. Second, an examination of time dynamics in the citation accumulation process reveals delayed recognition for novel research. Specifically, although novel papers are highly cited in the long run, they are less likely to be top cited in the short run. We also find that novel papers are less likely to be published in high Impact Factor journals. These findings suggest that over-reliance on standard bibliometric metrics, in particular Journal Impact Factor and short-term citation counts, may bias against novel research.

2. Combinatorial novelty in science

We view the process of research as one of puzzle solving, whereby researchers work with pieces of knowledge and combine them to generate new scientific knowledge. Some of these existing knowledge pieces are embedded in the literature, some in equipment and materials, which themselves are embedded in the literature, and others in the tacit knowledge of individuals engaged in the research. Using knowledge pieces in well-understood ways corresponds to a search process labeled as *exploitation*. Using existing knowledge pieces in new ways corresponds to an *explorative* search process, which is more likely to lead to major breakthroughs but also comes with a substantial risk of no or low impact (March, 1991). From this perspective, novel research is more closely associated with exploration.

Drawing on this combinatorial perspective of the research process, *novelty* can be defined as the recombination of pre-existing knowledge components in an unprecedented fashion. This

combinatorial view of novelty has been embraced by scholars in various disciplines (Arthur, 2009; Burt, 2004; Mednick, 1962; Schumpeter, 1939; Simonton, 2004; Weitzman, 1998). For example, Nelson and Winter (1982) state that “the creation of any sort of novelty in art, science or practical life – consists to a substantial extent of a recombination of conceptual and physical materials that were previously in existence.” Romer (1994) and Varian (2009) also argue that new combinations of existing components provide a potentially huge source of important new discoveries. The ability to make new combinations of existing knowledge pieces is one reason that “outsiders” from other disciplines arguably can provide exceptional insights when they move from one field to another, as physicist Leo Szilard did, when he switched from physics to biology in the 1950s (Carroll, 2013, p. 352).

It is important to note that not all breakthroughs result from combinatorial novelty, and certainly not all novel research leads to breakthroughs. It is also important to note that there is strong anecdotal evidence that research of a novel nature not only has the potential to become a breakthrough but also contributes to subsequent breakthroughs. The diagrams that Feynman produced in the late 1940s provided physicists with an entirely new way of understanding the behavior of subatomic particles and, according to the historian of physics David Kaiser, “have revolutionized nearly every aspect of theoretical physics” (Kaiser, 2009, p. 4). The creation of transgenic and knockout mice in the late 1980s revolutionized research on any number of diseases. Or, consider the research of Sebastian Seung that has received considerable attention and aims at mapping the human brain, something that no one to date has done (Cook, 2015). Seung’s course is heavily influenced by applying a method described in a highly-cited paper published in *PloS BIOLOGY* (Denk & Horstmann, 2004) that used a novel approach in human connectome (cf *infra*).

The combinatorial view of novelty has been studied in the technological invention literature and operationalized using patent information. Fleming (2001) takes the technology subclasses in which patents are classified as representing the components of technological know-how. Fleming (2007) looks at the occurrence of new combinations of subclasses to which a patent is assigned and uses this as a measure of the generative creativity of inventors of the patent. Verhoeven, Bakker, and Veugelers (2016) combine this combinatorial novelty measure with a measure of novelty in technological and scientific knowledge origins, based on whether the focal

patent cites other technological inventions or scientific literature from areas that were never cited before in its patent class. They find that the combination of the combinatorial novelty and the novelty in knowledge origins is a powerful identifier of breakthrough inventions.

Uzzi, Mukherjee, Stringer, and Jones (2013) apply a conceptually similar approach to scientific publications. They propose to trace the combinatorial process underlying the research from the references of the published paper. Operationally, they view journals as bodies of knowledge pieces and calculate the relative commonness for each pair of journals referenced by a paper. For this individual paper, they then use the lowest 10th percentile commonness score of its series of commonness scores as an indication of its “novelty” and the median commonness score as an indication of its “conventionality.” They find that papers with both high novelty and conventionality are more likely to become top cited. Lee, Walsh, and Wang (2015) adapt the Uzzi et al. (2013) measure for their study of creativity in scientific teams and find that team characteristics, i.e., size, and field and task variety, have different effects on novelty than on impact of the publication produced by the team.

Other approaches to assess combinatorial novelty in science also exist in the literature. Boudreau, Guinan, Lakhani, and Riedl (forthcoming), for example, identify whether a proposal to the NIH departs from the existing literature, by examining all possible pairs of MeSH (Medical Subject Headings) terms in the proposal and then calculating the fraction of the pairs which have not appeared in all the previous literature in PubMed. They find that evaluators systematically give lower scores to highly novel research proposals. Azoulay, Güler, Koçak, Murciano-Goroff, and Anttila-Hughes (2012) measure the recombinative character of a publication in a similar manner, examining the extent to which pairs of its MeSH descriptors are unusual. Using this measure, they find a positive relationship between the recombinative nature of a paper and the breadth of its citations but a negative relationship between the measure and citation volume.

Following the combinatorial novelty approach, we assess the novelty of a research article by examining the extent to which it makes novel combinations in prior knowledge components. In operationalizing the combinatorial novelty approach, we follow Uzzi et al. (2013) and use journals as bodies of knowledge components. Rather than looking at the *atypicality* of

referenced journal pairs as do Uzzi et al. (2013), we focus specifically on the *novelty* of referenced journal pairs by examining whether a pair has never been made in prior publications and is thus *new*. Furthermore, we take into account the knowledge distance between the newly-combined journals based on their co-cited journal profiles, i.e., their common “friends”, to assess the difficulty of making the new combination. More precisely, we measure the novelty of a paper as the number of new journal pairs in its references weighted by the cosine similarity between the newly-paired journals.

3. Measuring novelty of scientific publications

3.1.Procedure

We construct our novelty indicator for research articles published in 2001 and indexed in the Thomson Reuters Web of Science Core Collection (WoS), based on their references.

- For each paper, we retrieve all of its referenced journals and pair them up (i.e., J_1 - J_2 , J_1 - J_3 , J_1 - J_4 ...).
- We examine each journal pair to see whether it is new, i.e., has never appeared in prior literature starting from 1980¹.
- For those new journal pairs (e.g., J_1 - J_2), we assess how easy it is to make this new combination, by investigating how many common “friends” the paired journals have. More precisely, we compare the co-citation profiles of the two journals (J_1 and J_2) in the preceding three years (between year $t-3$ and $t-1$).
 - We use the following matrix where each row or column provides the co-citation profile for a journal. The i,j -th element in this symmetric matrix is the number of times that J_i and J_j are co-cited, that is, the number of papers published between year $t-3$ and $t-1$ that cite the two journals together. For example, in the preceding three years, the pair J_1 and J_2 have never been cited together by any papers (as this pair is new), but J_1 and J_3 have been cited together by 3 papers, and J_2 and J_3

¹ The 1980 cut off is because of data-availability reasons. It assumes a window of 20 years before obsolescence.

have been cited together by 6 papers, making J_3 a common friend of J_1 and J_2 , as is journal J_5 .

	J_1	J_2	J_3	J_4	J_5	...
J_1	/	0	3	0	5	...
J_2	0	/	6	2	3	...
J_3	3	6	/	5	4	...
J_4	0	2	5	/	0	...
J_5	5	3	4	0	/	...
...	/

- The ease of combining J_1 and J_2 is then defined as the *cosine similarity* between their co-citation profiles:

$$COS_{1,2} = \frac{J_1 \cdot J_2}{\|J_1\| \|J_2\|}$$

where J_1 and J_2 are row (or column) vectors. *Cosine similarity* is a classic measure of similarity between two vectors and is widely used in bibliometrics.

- Correspondingly, the difficulty score of combining J_1 and J_2 is: $1 - COS_{1,2}$.
- For each paper, we construct a continuous measure of combinatorial *novelty* as the sum of the difficulty scores of making the new combinations. Papers without new combinations get 0 by definition.

$$Novelty = \sum_{J_i-J_j \text{ pair is new}} (1 - COS_{i,j})$$

- We also construct two alternative measures for robustness tests (details in *Appendix III*): the maximum novelty score which focuses exclusively on the novelty score of the most distant new journal pair and the weighted share of new journal pairs in all pairs, which is essentially a means of normalizing our novelty measure for the number of all journal pairs.
- In addition, to avoid trivial combinations, we focus only on the most important journal combinations, i.e., we exclude 50 percent of the least cited journals (as measured in the preceding three years). To further reduce the likelihood of picking up trivial combinations, we impose as a condition that the new combination must be reused at least

once in the next three years. We check the robustness of the main results to these choices in *Appendix III*.

3.2.Illustration

We use the paper coauthored by Denk and Horstmann (2004), “Serial Block-Face Scanning Electron Microscopy to Reconstruct Three-Dimensional Tissue Nanostructure” published in *PLOS Biology* to illustrate and validate our novelty measure.

Denk’s team developed a method called *Serial Block-Face Scanning Electron Microscopy* (SBFSEM), which combines slicing and imaging by placing an *ultra-microtome* inside the chamber of a *scanning electron microscope*. The microscope scans the surface of the tissue block, and then the microtome shaves a thin slice off and exposes the next layer for a subsequent round of imaging. The researchers made a new and effective combination between an *environmental scanning electron microscope* and a special-designed *ultra-microtome*. While both components already existed and were in use, the combination is new. This new combination not only provides an automated method to collect serial images with sufficient resolution to trace even the thinnest axons and to identify connections between individual neurons but also overcomes many other problems. For example, it produces uninterrupted series of aligned images without section loss, contamination, or distortion, which often arise from manual sectioning and imaging. This work has opened the possibility of automatically generating serial images for reconstructing the neural network. It has also revitalized the dream of mapping the human brain and is contributing to the research of a number of scientists, including that of Sebastian Seung, mentioned *supra*.

The *PLOS Biology* paper cites 19 WoS-indexed journals. Of all possible journal pairs (171), 9 journal pairs are new, using the procedure described *supra*. Each of these new journal pairs involves an article from *Nature Materials* (subject categories: Chemistry, Physical; Materials Science, Multidisciplinary; Physics, Applied; and Physics, Condensed Matter), which is combined with articles from journals in subject categories of Neurosciences; Cell Biology; and Physiology. The *cosine similarity* for each of the 9 combinations is extremely low, indicating that each of the new combinations have few common friends and are therefore relatively difficult

to make. This leads to an overall score on novelty of 8.9891 for the Denk and Horstmann paper, which places the paper in the top 1% of novel papers in its field.

PLOS Biology (where the paper was published) had an Impact Factor of 13.868 in 2004, which ranked it in the upper quartile (Q1) in both of its subject categories: Biology and Biochemistry & Molecular Biology. The paper was not among the top 1% highly cited papers in the subject category of Biology until 2012 and in the subject category of Biochemistry & Molecular Biology until 2013. Papers citing it include several articles published in *Nature* and *Science*, some of which are top cited papers. *Appendix I* describes the calculation of the novelty score for the Denk and Horstmann paper in more details.

The Denk and Horstmann paper thus illustrates how research that is combinatorially novel has reference pairs that are new.

4. Data and descriptive statistics

To explore the properties of novelty and its relationship with impact, we use a dataset consisting of all research articles² in WoS published in 2001 from all the 251 subject categories. There are 773,311 articles in total, and 674,546 of them have at least two references to WoS journals. Among these 674,546 articles, 203 have no subject category information and therefore are also excluded, and 274,072 articles have more than one subject category (up to six subject categories) and are counted multiple times. The final 2001 dataset used has 1,056,936 observations.

We expect our measure to identify only a small minority of papers as novel, since the majority of research is of an exploitative rather than an exploratory nature. Indeed we find that relatively few papers make new referenced journal combinations. To be more specific, 89% of all papers in our sample make no new combinations of referenced journal and therefore do not score on the novelty measure. Of the 11% that make new journal combinations, most (55%) make only one new combination, and only 7% have more than 5 new combinations. Most of the novel papers score only modestly on our distance-weighted novelty indicator. At the other end of the distance

² Since we are interested in original research, we keep only publications labeled as “article” in WoS but exclude other document types such as “review” and “letter.”

distribution, we find the top 10 percentile to have a score on our distance weighted indicator in the range of the interval (5-248).

Insert Table 1 here

Overall, our measure of novelty displays a highly skewed phenomenon of novelty in scientific publications. We are particularly interested in papers which are highly novel. Therefore, we construct a categorical novelty variable *NOV CAT*: (1) *non-novel*, if a paper has no new journal combinations, (2) *moderately novel*, if a paper makes at least one new combination but has a novelty score lower than the top 1% of its subject category, and (3) *highly novel*, if a paper has a novelty score among the top 1% of its subject category.

Highly novel papers not only make more but also more distant new combinations. The median number of new combinations they make is 7, while the median for moderately novel papers is 1. In addition, the new combinations that highly novel papers make are more distant, as suggested by their lower *cosine similarity* scores compared with that of moderately novel papers (*Table 1*).

In addition, fields differ in their propensity to make new combinations. The Life Sciences score relatively higher, especially Neurosciences, Pharmacology and Biology & Biochemistry. The Physical Sciences score relatively low on novelty, especially Space Sciences and Physics. Social Sciences, especially Psychology, score above most fields³. Field difference in the novelty intensity may be partly explained by their heterogeneous patterns of publishing and referencing. In the econometric analysis we control for scientific field (i.e., WoS subject category) specific effects.

5. Novelty and impact

5.1.High risk of novel research

In view of the risky nature of novel research, we expect novel papers to have a higher variance in their citation performance. Following Fleming (2001), the Generalized Negative Binomial

³ By construction, there is no field differences in the relative share of highly novel (i.e., *NOV CAT* = 3) papers: *NOV CAT3* is defined as the top 1% novel papers within given subject categories.

(GNB) model is adopted to estimate the effects of novelty on the distribution characteristics of received citations. Specifically, GNB assumes that the number of citations (i.e., the dependent variable) follows a negative binomial distribution and allows us to model the natural logarithm of the mean μ and the natural logarithm of the dispersion parameter α each by a linear equation of novelty and other control variables. The variance of the distribution is $\sigma^2 = \mu + \alpha\mu^2$. For fitting the model the STATA function *gnbreg* is implemented (StataCorp, 2016).

We use a 14-year time window to count citations for our set of 2001 papers, which is deemed sufficiently long across fields (Wang, 2013). We control for other confounding factors with potential influence on the relationship between novelty and impact. First, we control for specific scientific field effects (cf supra), by including the complete set of dummies for the 251 WoS subject categories. Second, we control for the number of references made in the focal paper, which might increase both the likelihood of having new combinations and the number of received citations (Bornmann, Leydesdorff, & Wang, 2014; Lee et al., 2015)⁴. Third, we take into account the size and nature of the collaborative effort, which might affect both novelty and impact (Adams, Black, Clemmons, & Stephan, 2005; Katz & Hicks, 1997; Lee et al., 2015; Wang, Thijs, & Glänzel, 2015). Specifically, we include the number of authors and whether the paper is internationally coauthored as additional controls.

GNB model estimates are reported in *Table 2* and illustrated in *Figure 1A*. Compared with non-novel papers, *ceteris paribus*, moderately novel papers receive on average 2.78% more citations, and highly novel papers receive 12.04% more citations. At the same time, the higher average impact of novel papers is accompanied by a higher dispersion in citation performance. This holds however for only the highly novel papers. The dispersion of the citation distribution is 14.90% higher for highly novel papers than non-novel papers.

Insert Table 2 here

Insert Figure 1 here

⁴ Controlling for the number of references is particularly important, as our measure of novelty is not expressed as a share of all references.

A higher dispersion in impact can be driven by more extreme successes and/or more cases of uncited or rarely cited papers. Therefore, we examine in which tail of high and low impact the highly novel papers are more likely to be. We do this using multinomial logistic regression (*Table 3*). We classify papers, within the same WoS subject category and publication year, into three citation classes based on their citations in the 14-year time window: the top 10%, the lowest 10%, and the middle 80%. There is clear evidence that highly novel papers, which have a higher dispersion in their citations, are more likely to be in the tail of high impact, specifically, the odds of being the top 10% cited versus being the middle 80% cited are 16.80% higher for highly novel than non-novel papers. There is equally strong evidence that highly novel papers are more likely to be in the tail of least cited papers: the odds of being in the lowest 10% cited versus being in the middle 80% cited are 16.76% higher for highly novel than non-novel papers. In other words, the higher dispersion in citations for highly novel papers is driven by both tails of high and low impact and therefore reflects their higher level of uncertainty. On the other hand, moderately novel papers are only more likely to be in the top tail but not in the lower tail, displaying a lower level of uncertainty compared with highly novel papers, in line with the GNB results.

Insert Table 3 here

5.2.High gain from novel research

While novel research faces a higher level of risk, we also expect, as argued supra, novel research to have a higher probability of making a significant contribution to research. We first examine whether novel papers are more likely to become “big hits,” i.e., receive an exceptionally large number of citations, defined here, following the bibliometric convention, as being top 1% highly cited in the same WoS subject category and publication year. Logistic regression controlling for previously mentioned other potential confounding factors reveals that the odds of a big hit are 39.82% higher for highly novel papers and 11.22% higher for moderately novel papers, compared with comparable non-novel papers (*Table 4* column 1 and *Figure 1B*).

Insert Table 4 here

Second, we find that novel papers are more likely to be cited by other big hits. Novel research is therefore not only more likely to become a big hit itself but also more likely to stimulate follow-on research which generates major impact. Specifically, we find that papers that cite novel papers are more likely to themselves receive more citations, compared with papers citing non-novel papers (*Appendix II Table A3*). Likewise, the probability of being cited by an article which itself becomes a big hit is also higher for highly novel papers than for non-novel papers. We use a logistic model to estimate the probability of a paper being cited by big hits, teasing out any contamination from direct citations received, in addition to controlling for previously mentioned other confounding factors. We observe that the odds of being cited by big hits are 26.20% higher for a highly novel paper than for comparable non-novel papers receiving the same number of citations (*Table 4 column 2 and Figure 1C*)⁵. Compared with highly novel papers, moderately novel papers demonstrate a much smaller advantage over non-novel papers. The odds of being cited by big hits are 3.56% higher for a moderately novel paper than a comparable non-novel paper.

5.3. Transdisciplinary impact of novel research

We explore the breadth of impact, that is, whether novel research is cited across more scientific fields than is non-novel research. We use the number of subject categories citing the focal paper in the 14 years after publication as the dependent variable and estimate a Poisson model. The Poisson model additionally controls for the number of citations, given that papers with more citations are more likely to be cited by more fields. Results show that, compared with non-novel papers receiving the same number of citations and having the same values on all other control variables, highly and moderately novel papers are cited by 16.56% and 10.05% more subject categories, respectively (*Table 4 column 3 and Figure 1D*).

⁵ In this analysis, big hits, which cite the focal paper, are identified as the top 1% highly cited papers in the same subject category and publication year, based on their cumulative citations till the end of 2014. Given that we do not have a sufficiently long time window to count citations for very recent papers, we only account for big hits between 2001 and 2009 and accordingly test whether novel papers are more likely to be cited by big hits in the 9-year period from 2001 to 2009. Correspondingly, we control for the number of direct citations in the same 9-year period.

We examine whether the impact of a novel paper is more likely to be outside its own field than within its own field. To this end, we partition a paper's forward citations into two types: "home" and "foreign" field citations, that is, citations received from subsequent publications that share at least one common WoS subject category (home field citations) and citations from publication that share no common WoS subject categories (foreign field citations). Then we calculate, for each paper, the proportion of its citations that are foreign field citations. An OLS model (*Table 4* column 4) shows that novel papers have a larger ratio of citations from foreign fields, suggesting that novel research has a greater transdisciplinary impact than does non-novel research⁶.

The broader and more transdisciplinary impact of novel research raises the question of whether the major impact that novel papers generates is driven by their impact within and/or outside their own field. To answer this question we examine separately whether novel papers are among the top 1% highly cited in their home field and in foreign fields (*Table 4* columns 5-6 and *Figure 1E*)⁷. We find that the odds of being top cited in home fields are not significantly larger for highly novel papers than non-novel papers, and for moderately novel papers they are even 8.37% lower compared with that of non-novel papers. The lower chance for novel papers to be highly cited in their home field is consistent with resistance from existing paradigms against novel approaches. At the same time, novel papers, compared with non-novel ones, have higher odds of being highly cited in foreign fields. Although this holds for moderately novel papers, it especially holds for highly novel papers, i.e., the odds of being highly cited in foreign fields are 29.39% and 62.37% higher for moderately and highly novel papers respectively, compared with that of non-novel papers. The finding that the overall high impact of novel research is due to its success in foreign fields rather than in its home field calls to mind the passage from Luke 4:24: "Verily I say unto you, No prophet is accepted in his own country."

⁶ The findings that novel papers has an impact which is broader and more transdisciplinary (i.e., are cited by more fields and have a larger ratio of foreign field citations) are robust when we additionally control for the number of WoS subject categories that the focal paper itself is affiliated with (*Appendix II Table A4*).

⁷ It is important to note that a paper being highly cited in foreign fields means that, compared with other papers in the same WoS subject category and publication year, its number of citations from foreign fields is among the top 1% highest. It does not mean that this paper is among the top 1% highly cited in a specific foreign field compared with all other papers based on their citations in this specific field.

5.4. Delayed recognition for novel research

The major impact of novel research may take longer to realize, for instance, because of resistance from existing paradigms. To explore the extent to which delays in recognition occur, we estimate the probabilities of being a top 1% highly cited paper for non-, moderately-, and highly- novel papers for citation windows ranging from 1 to 14 years. We find that highly novel papers are less likely to be top cited when using citation time windows shorter than 3 years (*Table 5, Figure 1F, and Figure 2A*). As of the fourth year after publication, highly novel papers are significantly more likely to be top cited, and their advantage over non-novel papers increases with the length of the time window. Moderately novel papers suffer even more from delayed recognition. They are less likely to be top cited when using citation windows shorter than 5 years, and they only have a significantly higher chance of being a big hit with windows of at least 9 years.

Insert Table 5 here

Insert Figure 2 Here

The well-known fact that it takes longer for papers in one field to be cited in another field (Rinia, Van Leeuwen, Bruins, Van Vuren, & Van Raan, 2002) raises the question of whether the finding of delayed recognition for novel research is driven by their large share of citations that come from foreign fields. We unravel the delayed recognition results further by comparing the time profile in recognition separately for home and foreign fields. A number of interesting results emerge.

First, the lower impact which novel papers face in their home field compared with non-novel papers shrinks over time, showing that delayed recognition for novel papers exists in their home field (*Appendix II Table A5 and Figure 2B*). More specifically, we find that highly novel papers, compared with non-novel papers, are significantly less likely to be top cited in their home field in the first five years, but this disadvantage disappears when using a longer window. Moderately novel papers, however, are consistently, over time, significantly less likely to be top cited in their home field compared with non-novel papers. Nevertheless, the gap with non-novel papers in the

probability of being top cited in the home field shrinks over time for moderately novel papers, just as it does for highly-novel papers.

Second, the higher impact of novel papers in foreign fields compared with non-novel papers magnifies over time, suggesting the delayed recognition for novel papers also exists in foreign fields (*Appendix II Table A6* and *Figure 2C*). We find that both moderately and highly novel papers are more likely to be highly cited in foreign fields than non-novel papers, but this advantage requires a citation time window of at least three and four years for highly and moderately novel papers, respectively. Moreover, the foreign advantage of novel papers clearly increases over time.

Third, as *Appendix II Figure A1* shows, impact in foreign fields takes longer to materialize than that in home fields. For all papers, regardless of novelty, the average number of annual citations in foreign fields, compared with that of home fields, is smaller in the first seven years but greater in later years. This implies that it takes time for larger success of novel papers in foreign fields to compensate for their lack of advantage in their home fields. This is illustrated by *Appendix II Figure A2* which shows that it takes time for the advantage that novel papers enjoy in foreign fields to cancel out any disadvantage they have in home fields. In sum, the overall delayed recognition for novel papers is a composite effect consisting of a delayed recognition both in home as well as in foreign fields and a delayed process in knowledge diffusion to other fields.

5.5. Bias against novelty

The finding of delayed recognition for novel research bears direct implications on the use of bibliometric indicators in science policy. As novel papers suffer from delayed recognition and need a sufficiently long citation time window before reaching the status of big hit, standard bibliometric indicators which use short citation time-windows (typically two or three years) are biased against novelty.

In this section, we explore further how novel research performs on standard bibliometric indicators, beyond the bias generated by short citation windows. Specifically, we examine the *Journal Impact Factor*, probably the most commonly used and influential bibliometric indicator for assessing the quality of journals and their articles. We investigate whether novel papers, with

their “high risk/high gain” nature, are more or less likely to be published in high Impact Factor journals. We find that although novel papers are published on average in journals with higher Impact Factors, compared with non-novel ones (*Appendix II Table A2*), the Poisson regression, controlling for other confounding factors such as field differences, reveals that the Journal Impact Factor of moderately- and highly-novel papers is significantly and substantially lower (approximately 10.55% and 18.11% respectively) than comparable non-novel papers (*Table 6* and *Figure 3*). This finding – that novel papers are published in journals with Impact Factors below their potential – suggests that novel papers encounter obstacles in being accepted by journals holding central positions in science. Moreover, the negative association between novelty and Journal Impact Factor is not due to novel papers being more likely to be published in new journals. Regression analyses which additionally control for journal age or whether the journal is new confirms that novel papers are published in lower Impact Factor journals than expected (*Table 5*). The increased pressure journals are under to boost their Impact Factor (Martin, 2016) and the fact that the Journal Impact Factor is based on citations in the first two years after publication⁸ suggests that journals may strategically choose to not publish novel papers which are less likely to be highly cited in the short run.

Insert Table 6 here

Insert Figure 3 here

Another question is whether the negative association between novelty and Journal Impact Factor is responsible for the delayed recognition faced by novel research. To address this question, we examine whether the novelty effect on the probability of big hits is contingent on the Journal Impact Factor. If publication in a low Impact Factor journal is responsible for the delayed recognition encountered by novel papers, we expect that novel papers which succeed in getting in high Impact Factor journals would not suffer from delayed recognition. Therefore, we re-estimate the models in *Table 5*, additionally controlling for the Journal Impact Factor and incorporating interaction effects between novelty and whether the journal in which the focal paper is published has a top 10% Impact Factor in its subject category. As shown in *Appendix II*

⁸ Journal Impact factor is essentially the average number of citations received in the current year by papers published in the preceding two years. <http://wokinfo.com/essays/impact-factor/>

Table A7 and *Figure 4*, novel papers published in high Impact Factor journals still have a delayed citation accumulation process compared with non-novel papers in high Impact Factor journals. We conclude that delayed recognition is not entirely due to publication of novel works in journals with lower than expected Impact Factors.

Insert Figure 4 here

5.6. Novelty and quality

Our research demonstrates that standard bibliometric indicators, especially short-term citation windows and the Journal Impact Factor, are biased against novel papers. One might argue that such “bias” simply reflects the low quality associated with novel research. This raises the potential issue concerning unobserved and uncontrolled heterogeneity in paper quality. If novel research is associated with low quality, this would indeed explain the observation that novel papers are less likely to be highly cited in the short run and are less likely to be published in high Impact Factor journals, but it cannot explain why novel papers are more likely to eventually become highly cited and be cited in broader fields. On the other hand, if novel research is associated with high quality, then it would explain its long-term big impact but not its delayed recognition, or its lower Journal Impact Factor, or the fact that novel papers which are published in high Impact Factor journals still display a delayed recognition. Although we cannot completely rule out the possible link between novelty and quality, due to the lack of a proper measure for the true *ex ante* quality of a paper, the citation patterns of novel research that we find in this paper suggest something different than a clear association between novelty and quality. Therefore, we can at least conclude that novelty affects *ex post* impact in a non-trivial fashion which is difficult to explain by *ex ante* quality.

5.7. Robustness analysis

We ran a set of robustness tests on our findings. Details are reported in *Appendix III*. First, we tested whether our findings are robust across scientific fields. All our findings are robust for hard sciences and engineering, but several findings are not robust for social sciences and humanities. Although this may suggest that our findings hold only for hard sciences, it is more likely due to the insufficient coverage of WoS for humanities and social sciences (Hicks, 2004).

Second, we examined whether our findings are sensitive to variations of our novelty measure. Our novelty measure is essentially a distance-weighted number of new combinations, and we tested two alternative formulations, i.e., the maximum novelty score which focuses exclusively on the novelty score of the most distant new journal pair and the weighted share of new journal pairs in all pairs, which is essentially a means of normalizing our novelty measure for the number of all journal pairs. Results are consistent when using these alternative formulas.

Our novelty measure excluded 50% of the least cited journals and required that the new combination of journals is reused in the next three years. Relaxing these constraints yielded robust results. Our results are also robust to additional constraints, such as excluding top 10% highly cited journals and multidisciplinary journals.

We used categorical novelty measures in our regression analysis (i.e., highly-, moderately-, and non-novel). We duplicated the results using the natural logarithm transformed continuous novelty score in the regression and obtained robust results. We classified papers with the highest 1% novelty score as highly novel. Using alternative thresholds, i.e., top 0.1% and 5%, also yielded consistent results.

Third, all our findings remain consistent and significant when we additionally control for the Uzzi et al. (2013) measure of *atypicality* in the regressions. More importantly, compared with Uzzi et al. (2013) measure of *atypicality*, our novelty measure behaves more reliably and captures more the “high risk” nature of novel research.

6. Discussion

We propose that a way to measure the potential an article has to advance the knowledge frontier is to examine the combinatorial novelty of its references. To this end, we apply a newly minted measure of novelty to all WoS research articles published in 2001 across all scientific disciplines. We find that novel papers, in particular highly novel papers, exhibit citation patterns consistent with the “high risk/high gain” profile associated with breakthrough research. Novel papers have a higher variance in citation performance than do non-novel papers, confirming their risky profile. At the same time, novel papers are associated with big hits. They have a much higher chance of being top 1% highly cited, and are more likely to lead to follow-up high impact

research. Novel papers also have a broader impact across scientific fields, and are more likely to be highly cited in foreign fields compared with non-novel papers but not more likely to be highly cited in their home fields. Furthermore, novel papers require a sufficient period of time before their important contribution is recognized. This delayed recognition is suggestive of reluctance from incumbent scientific paradigms to recognize novel approaches and the longer time period needed to incorporate novel research into subsequent research. Part of the delayed recognition is due to the time it takes for novel research to diffuse to other fields, where they have their greatest impact.

Delayed recognition leads novel research to perform poorly on classic bibliometric measures which use short citation windows. Novel research is also published in journals with lower than expected Impact Factors, another classic bibliometric measure. Moreover, even if novel research succeeds in being published in high impact factor journals, it still suffers from delayed recognition.

Taken together, our results suggest that standard bibliometric measures are biased against novel research and thus may fail to identify papers and individuals doing novel research. This bias against novelty imperils scientific progress, because novel research, as we have shown, is much more likely to become a big hit in the long run in fields outside its own, as well as to stimulate follow-up big hits.

The bias against novelty is of particular concern given the increased reliance funding agencies place on classic bibliometric indicators in making funding and evaluation decisions. The bias against novel papers may also help explain why funding agencies which increasingly rely on bibliometric measures are widely perceived as being more and more risk-averse, choosing “safe” projects over those that involve a higher level of uncertainty with regard to possible outcomes. In this respect, our research is consistent with that of Boudreau et al. (forthcoming) who find that evaluators give lower scores to proposals that are highly novel where novelty is measured in terms of the proposal’s use of novel combinations of MeSH terms relative to the underlying literature.

The bias against novelty applies not only to funding decisions but to science policy more generally. The prevailing use in various decisions (e.g., hiring and tenure of researchers) at

various levels (i.e., department, university, and national) of standard bibliometric indicators which rely on short citation time windows and Journal Impact Factor is likely to disincentivize novel research. We advocate the awareness of such potential bias and suggest, when relying on bibliometric indicators, to use a wider portfolio of indicators and, when using standard measures, time windows beyond two or three years.

In addition, the finding that novel papers are highly cited in foreign fields but not in their home field highlights the importance of avoiding a monodisciplinary approach in peer review. Peer review is widely implemented in science decision-making. It is typically organized along disciplinary lines, with peers within the same discipline making a judgment on the value of the research that is being evaluated. Studies of interdisciplinary research demonstrate that a discipline-based science system is detrimental to the advancement and societal accountability of science (Gibbons, 1994; The National Academies, 2004). This paper contributes to this discussion, suggesting that peer review which is bounded by disciplinary borders may fail to recognize the full value of novel research which typically lies outside its own field.

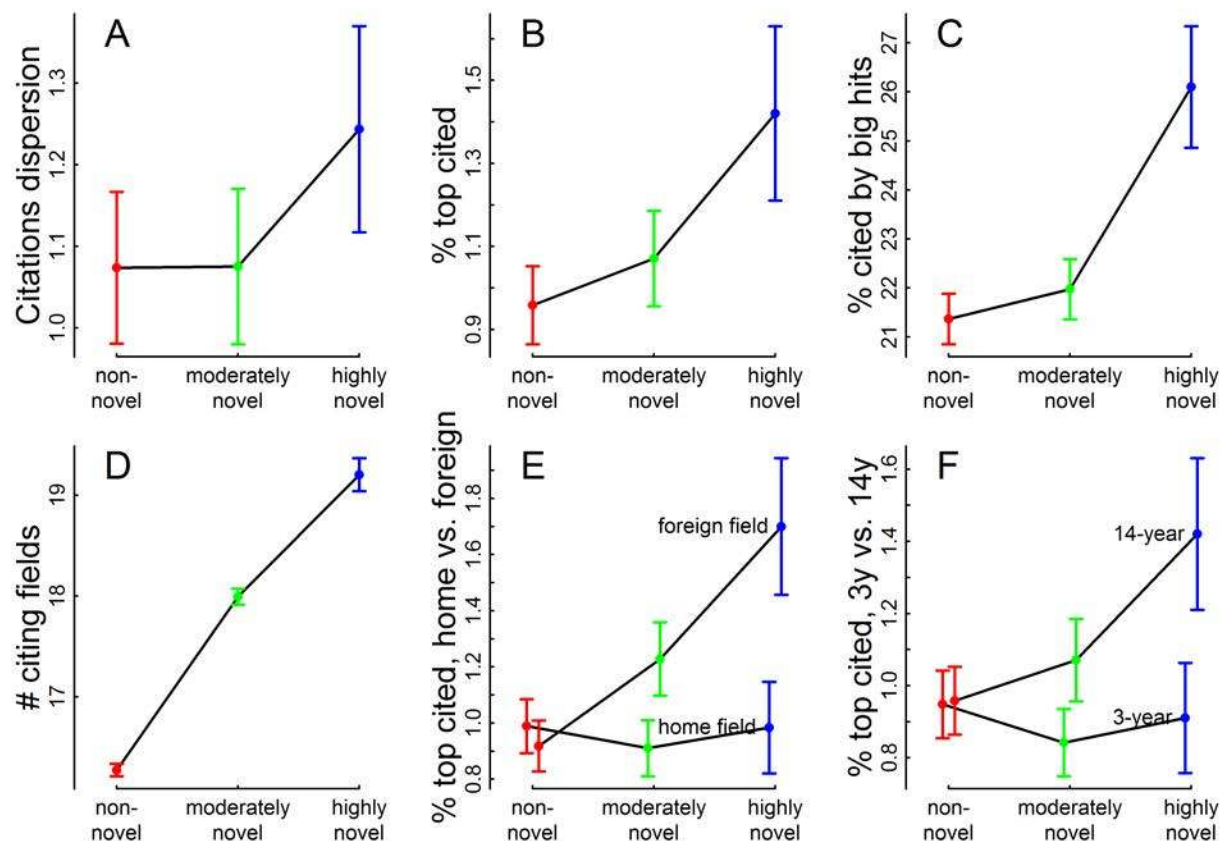


Figure 1. Impact profile of novel research. (A) Estimated dispersion of citations (14-year), based on the Generalized Negative Binomial model in *Table 2* column 3. (B) Estimated probability of being among the top 1% cited articles in the same WoS subject category and publication year, based on 14-year citations and the logit model in *Table 4* column 1. (C) Estimated probability of being cited by big hits, based on the logit model in *Table 4* column 2. (D) Estimated number of WoS subject categories citing the focal paper (14-year), based on the Poisson model in *Table 4* column 3. (E) Estimated probability of being among the top 1% cited articles in the same WoS subject category and publication year, based on 14-year home and foreign field citations separately. Estimations are based on two logit models in *Table 4* column 5 and 6. (F) Estimated probability of being among the top 1% cited articles in the same WoS subject category and publication year, based on 3-year and 14-year citations separately. Estimations are based on two logit models in *Table 5* column 3 and 14. All estimated values are for an average paper (i.e., in the biggest WoS subject category, not internationally coauthored, and with all other covariates at their means) in different novel classes. The vertical bars represent the 95% confidence interval. Data consist of 1,056,936 WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection.

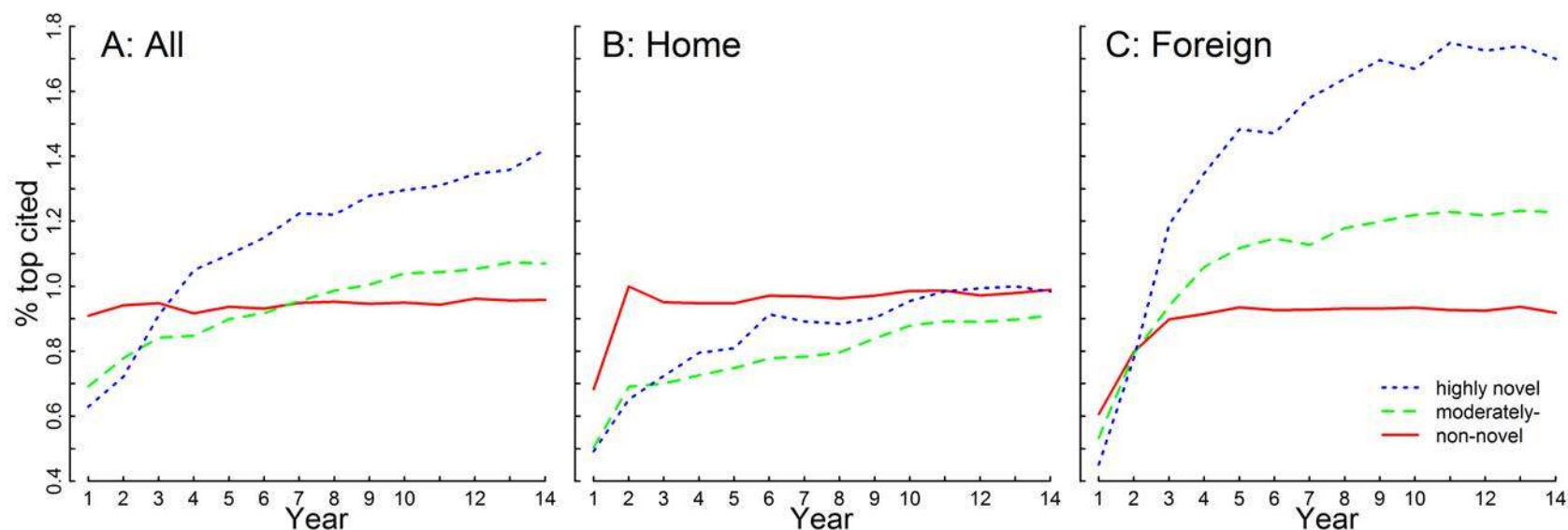


Figure 2. Citation dynamics and novelty. (A) Estimated probability of big hits, using 14 consecutive time windows to dynamically identify big hits. As an example, big hits in year 3 are identified as the top 1% highly cited papers based on their cumulative citations in a 3-year time window, i.e., from 2001 to 2003. Results are based on 14 logistic models reported in *Table 5*. (B) Estimated probability of big hits, based on home field citations, i.e., citations received from papers sharing at least one common WoS subject category with the focal cited paper. Results are based on 14 logistic models reported in *Table A5*. (C) Estimated probability of big hits, based on foreign field citations, i.e., citations received from papers sharing no common WoS subject categories with the focal cited paper. Results are based on 14 logistic models reported in *Table A6*. Data consist of 1,056,936 WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection.

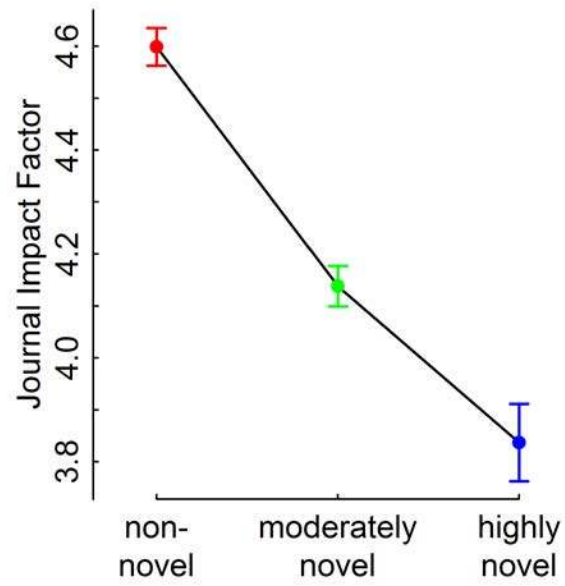


Figure 3. Journal Impact Factor and novelty. Estimated Journal Impact Factor for an average paper with different novelty classes, based on the Poisson model reported in *Table 6* column 3. Data consist of 1,056,936 WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection.

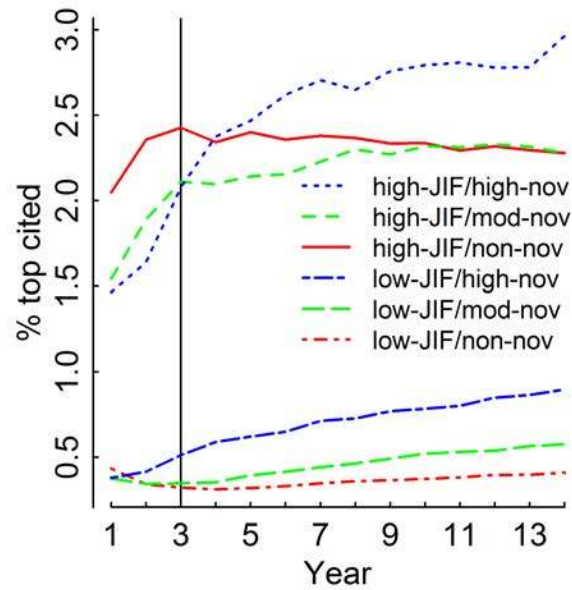


Figure 4. Citation dynamics and novelty, by JIF groups. Estimated probability of being a big hit by year, for papers in different novelty classes and Journal Impact Factor groups. Estimations are based on a set of logistic models additionally incorporating interaction effects between novelty classes and whether a journal has an Impact Factor among the top 10% in its field. Regression outputs are reported in *Appendix II Table A7*. Data consist of 1,056,936 WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection.

Table 1. Occurrence of novelty

	(1)	(2)	(3)	(4)	(5)	(6)
	Number of papers	% of all papers	Avg (avg cos)	Avg(min cos)	Avg # new pairs	Median # new pairs
non-novel	942850	89%	/	/	/	/
moderately novel	103418	10%	0.0015	0.0013	1.7055	1
highly novel	10668	1%	0.0009	0.0004	7.9499	7

Data sourced from Thomson Reuters Web of Science Core Collection.

Table 2. Mean and dispersion of citations

	Citations (14-year)		
		GNB	
	(1)	(2)	(3)
Mean			
Novelty	0.0376*** (0.0050)		
Novel (dummy)		0.0407*** (0.0056)	
NOV CAT2			0.0310*** (0.0058)
NOV CAT3			0.1294*** (0.0179)
International	0.0766*** (0.0052)	0.0765*** (0.0052)	0.0765*** (0.0052)
Authors (ln)	0.2714*** (0.0046)	0.2712*** (0.0046)	0.2713*** (0.0046)
Refs (ln)	0.6310*** (0.0057)	0.6319*** (0.0057)	0.6306*** (0.0057)
Dispersion			
Novelty	0.0381*** (0.0065)		
Novel (dummy)		0.0164* (0.0073)	
NOV CAT2			0.0016 (0.0076)
NOV CAT3			0.1468*** (0.0218)
International	-0.0670*** (0.0072)	-0.0672*** (0.0072)	-0.0670*** (0.0072)
Authors (ln)	-0.1468*** (0.0056)	-0.1468*** (0.0057)	-0.1468*** (0.0056)
Refs (ln)	-0.2515*** (0.0068)	-0.2476*** (0.0068)	-0.2495*** (0.0068)
N	1056936	1056936	1056936
Log lik	-4310346	-4310403	-4310298
Chi2	126125***	125932***	126118***

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** p<.001, ** p<.01, * p<.05, + p<.10.

Table 3. Citation classes

	Citation classes (14-year) Multinomial logit
<hr/>	
Top 10% vs. middle 80%	
NOV CAT2	0.0567*** (0.0103)
NOV CAT3	0.1680*** (0.0258)
International	0.0846*** (0.0083)
Authors (ln)	0.4607*** (0.0063)
Refs (ln)	1.0592*** (0.0068)
<hr/>	
Low 10% vs. middle 80%	
NOV CAT2	-0.0562** (0.0163)
NOV CAT3	0.1676** (0.0557)
International	-0.2372*** (0.0126)
Authors (ln)	-0.5983*** (0.0076)
Refs (ln)	-1.0716*** (0.0068)
<hr/>	
N	1056936
Log lik	-535824
Chi2	1800000***

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. We classify papers, within the same WoS subject category and publication year, into three classes based on their 14-year citations: low 10%, middle 80%, and top 10%. For the multinomial logit regression, the middle 80% is used as the reference group. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** p<.001, ** p<.01, * p<.05, + p<.10.

Table 4. Impact profile of novel research

	(1)	(2)	(3)	(4)	(5)	(6)
	Top 1% cited (14-year)	Cited by big hits (9-year)	# citing fields (14-year)	Ratio foreign field citations (14-year)	Top 1% cited home field (14-year)	Top 1% cited foreign field (14-year)
	logit	logit	Poisson	OLS	logit	logit
NOV CAT2	0.1122*** (0.0287)	0.0356** (0.0110)	0.1005*** (0.0013)	0.0489*** (0.0009)	-0.0837** (0.0307)	0.2939*** (0.0279)
NOV CAT3	0.3982*** (0.0593)	0.2620*** (0.0292)	0.1656*** (0.0039)	0.0821*** (0.0025)	-0.0052 (0.0706)	0.6237*** (0.0563)
9-year citations (ln)		1.8363*** (0.0051)				
14-year citations (ln)			0.5548*** (0.0007)	0.0030*** (0.0003)		
International	0.0681** (0.0240)	0.0037 (0.0089)	-0.0120*** (0.0011)	-0.0054*** (0.0007)	0.0801** (0.0243)	0.0600* (0.0245)
Authors (ln)	0.5539*** (0.0182)	-0.0648*** (0.0066)	0.0022* (0.0009)	0.0122*** (0.0005)	0.5177*** (0.0183)	0.5436*** (0.0184)
Refs (ln)	1.2074*** (0.0206)	-0.1143*** (0.0071)	0.0107*** (0.0010)	0.0062*** (0.0005)	1.2136*** (0.0206)	1.1586*** (0.0208)
N	1056929	1056565	1056918	990479	1056146	1056146
Log lik	-56424	-266709	-2635145	/	-55156	-54878
Chi2	5445***	145503***	1746164***	/	4823***	5518***
R2	/	/	/	0.1276	/	/

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. Top 1% cited (column 1) means being among the top 1% highly cited within the same WoS subject category and publication year, based on the number of citations in a 14-year time window between 2001 and 2014. Cited by big hit (column 2) means cited by an article, which is published in between 2001 and 2009 and among the top 1% highly cited articles within the same WoS subject category and publication year, based on their cumulative citations up to 2014. Big hits published after 2009 are not analysed because their available time windows are too short to identify big hits reliably. # citing fields (column 3) is the number of WoS subject categories citing the focal paper. Ratio foreign field citations (column 4) is the proportion of all citations that are from papers sharing no common WoS subject categories with the focal cited paper. Top 1% cited home field (column 5) means being among the top 1% highly cited within the same WoS subject category and publication year, based on 14-year citation received from papers that share at least one common WoS subject category with the focal cited paper. Top 1% cited foreign field (column 6) means being among the top 1% highly cited within the same WoS subject category and publication year, based on 14-year citation received from papers that share no common WoS subject category with the focal cited paper. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** p<.001, ** p<.01, * p<.05, + p<.10.

Table 5. Big hits and novelty: Delayed recognition

	Top 1% cited (1y) logit	Top 1% cited (2y) Logit	Top 1% cited (3y) logit	Top 1% cited (4y) logit	Top 1% cited (5y) logit	Top 1% cited (6y) logit	Top 1% cited (7y) logit	Top 1% cited (8y) logit	Top 1% cited (9y) logit	Top 1% cited (10y) logit	Top 1% cited (11y) logit	Top 1% cited (12y) logit	Top 1% cited (13y) logit	Top 1% cited (14y) logit
NOV	-0.2754***	-0.1919***	-0.1196***	-0.0790*	-0.0412	-0.0147	0.0051	0.0358	0.0613*	0.0916**	0.1021***	0.0908**	0.1171***	0.1122***
CAT2	(0.0398)	(0.0332)	(0.0314)	(0.0306)	(0.0299)	(0.0296)	(0.0294)	(0.0292)	(0.0289)	(0.0287)	(0.0287)	(0.0288)	(0.0286)	(0.0287)
NOV	-0.3709***	-0.2682**	-0.0405	0.1366*	0.1607*	0.2133**	0.2572***	0.2510***	0.3048***	0.3136***	0.3315***	0.3397***	0.3557***	0.3982***
CAT3	(0.1043)	(0.0828)	(0.0715)	(0.0655)	(0.0641)	(0.0626)	(0.0619)	(0.0623)	(0.0609)	(0.0610)	(0.0606)	(0.0604)	(0.0602)	(0.0593)
International	0.2324***	0.1973***	0.1400***	0.1181***	0.1002***	0.1036***	0.0992***	0.0913***	0.0927***	0.0946***	0.0877***	0.0674**	0.0593*	0.0681**
al	(0.0280)	(0.0245)	(0.0240)	(0.0239)	(0.0237)	(0.0237)	(0.0237)	(0.0238)	(0.0238)	(0.0238)	(0.0238)	(0.0238)	(0.0240)	(0.0240)
Authors	0.6041***	0.7648***	0.8207***	0.7973***	0.7659***	0.7485***	0.7249***	0.6932***	0.6613***	0.6363***	0.6139***	0.5877***	0.5754***	0.5539***
(ln)	(0.0209)	(0.0192)	(0.0187)	(0.0185)	(0.0181)	(0.0181)	(0.0180)	(0.0179)	(0.0179)	(0.0180)	(0.0180)	(0.0181)	(0.0181)	(0.0182)
Refs (ln)	0.9759***	1.2277***	1.2835***	1.2977***	1.3013***	1.2958***	1.2779***	1.2583***	1.2491***	1.2380***	1.2282***	1.2259***	1.2209***	1.2074***
	(0.0241)	(0.0220)	(0.0215)	(0.0213)	(0.0208)	(0.0208)	(0.0208)	(0.0207)	(0.0206)	(0.0207)	(0.0206)	(0.0207)	(0.0207)	(0.0206)
N	1052801	1055915	1056516	1056757	1056778	1056574	1056703	1056803	1056895	1056781	1056813	1056902	1056895	1056929
Log lik	-41211	-50133	-52495	-53555	-54675	-55026	-55249	-55582	-55858	-55849	-56074	-56209	-56275	-56424
Chi2	3753***	5871***	6745***	6815***	6919***	6858***	6604***	6300***	6195***	5967***	5780***	5613***	5543***	5445***

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. Big hits using a t -year time window means among the top 1% highly cited papers within the same WoS subject category and publication year, based on their citations in the t -year time window starting from 2001. Identifying big hits using annual citation counts instead of cumulative citation counts yields similar results. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** $p < .001$, ** $p < .01$, * $p < .05$, + $p < .10$.

Table 6. Journal Impact Factor and novelty

	(1) Journal age Poisson	(2) Jnl Age <4 logit	(3) JIF Poisson	(4) JIF Poisson	(5) JIF Poisson	(6) JIF TOP 10% logit	(7) JIF TOP 10% logit	(8) JIF TOP 10% logit
NOV CAT2	-0.0781*** (0.0027)	0.1119*** (0.0145)	-0.1055*** (0.0031)	-0.0839*** (0.0031)	-0.1033*** (0.0031)	-0.2013*** (0.0093)	-0.1551*** (0.0094)	-0.1984*** (0.0093)
NOV CAT3	-0.1673*** (0.0079)	0.3551*** (0.0388)	-0.1811*** (0.0092)	-0.1352*** (0.0088)	-0.1744*** (0.0091)	-0.3897*** (0.0268)	-0.2767*** (0.0273)	-0.3794*** (0.0269)
Journal age (ln)				0.2211*** (0.0013)			0.6778*** (0.0046)	
Journal age < 4					-0.3421*** (0.0048)			-0.5875*** (0.0150)
International	0.0357*** (0.0019)	-0.0835*** (0.0117)	0.0737*** (0.0024)	0.0651*** (0.0023)	0.0724*** (0.0023)	0.1309*** (0.0069)	0.1122*** (0.0070)	0.1289*** (0.0069)
Authors (ln)	0.0413*** (0.0013)	-0.1191*** (0.0078)	0.1735*** (0.0018)	0.1602*** (0.0017)	0.1712*** (0.0018)	0.4529*** (0.0051)	0.4366*** (0.0052)	0.4499*** (0.0051)
Refs (ln)	0.1091*** (0.0013)	-0.1366*** (0.0072)	0.3519*** (0.0017)	0.3250*** (0.0016)	0.3496*** (0.0017)	0.8863*** (0.0053)	0.8446*** (0.0054)	0.8836*** (0.0053)
N	1056936	1029027	1056936	1056936	1056936	1054940	1054940	1054940
Log lik	-8153953	-220326	-1716396	-1680856	-1711208	-428264	-411420	-427354
Chi2	191087***	23417***	942910***	1169732***	966429***	78384***	92594***	78492***

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. Results of Poisson models are reported here, an alternative specification, using the OLS model and the log of journal age or JIF as the dependent variable yields consistent results. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** p<.001, ** p<.01, * p<.05, + p<.10.

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Appendix I: Indicator illustration

We use the paper coauthored by Denk and Horstmann (2004), “Serial Block-Face Scanning Electron Microscopy to Reconstruct Three-Dimensional Tissue Nanostructure” published in *PLOS Biology* to illustrate our novelty measure. This paper cites 19 WoS-indexed journals. Of all possible journal pairs (171), 9 journal pairs are new, using the procedure described supra.

Pair	Journal 1	Journal 2	Novelty
1	NATURE MATERIALS	CURRENT OPINION IN NEUROBIOLOGY	0.9992
2	NATURE MATERIALS	DEVELOPMENTAL DYNAMICS	0.9991
3	NATURE MATERIALS	PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY OF LONDON SERIES B-BIOLOGICAL SCIENCES	0.9984
4	NATURE MATERIALS	EUROPEAN JOURNAL OF NEUROSCIENCE	0.9992
5	NATURE MATERIALS	JOURNAL OF HISTOTECHNOLOGY	0.9986
6	NATURE MATERIALS	SCANNING	0.9980
7	NATURE MATERIALS	BRAIN RESEARCH REVIEWS	0.9994
8	NATURE MATERIALS	ANNUAL REVIEW OF BIOPHYSICS AND BIOENGINEERING	0.9978
9	NATURE MATERIALS	PFLUGERS ARCHIV-EUROPEAN JOURNAL OF PHYSIOLOGY	0.9992

Each of these new journal pairs involves an article from *Nature Materials* (subject categories: Chemistry, Physical; Materials Science, Multidisciplinary; Physics, Applied; and Physics, Condensed Matter), being combined with articles from journals in subject categories of Neurosciences; Cell Biology; and Physiology. In the next step we calculate the *cosine similarity* for each journal pair, based on their profile of co-cited journals in the preceding three years (i.e., 2001-2003).

The co-citation matrix between all journals in the database is reported in the following table, based on the co-citation information in the preceding three years, i.e., 2001-2003. One entry represents the number of times that two corresponding journals are co-cited in the preceding three years. For example, *NATURE MATERIALS* has not been cited together with *CURRENT OPINION IN NEUROBIOLOGY* by any papers published between 2001 and 2003, but has been cited together with *SCIENCE* by 331 papers.

	J ₁	J ₂	J ₃	J ₄	J ₅	...	J _N
J ₁ NATURE MATERIALS	/	0	331	110	0	...	...
J ₂ CURRENT OPINION IN NEUROBIOLOGY	0	/	9691	0	9959	...	...
J ₃ SCIENCE	331	9691	/	...	...	...	...
J ₄ NANO LETTERS	110	0	...	/	...	...	...
J ₅ JOURNAL OF NEUROSCIENCE	0	9959	...	...	/	...	...
...	/	...
J _N	...	...	...	...	...	...	/

Using the *cosine similarity* score, the ease of combining *NATURE MATERIALS* and *CURRENT OPINION IN NEUROBIOLOGY* is:

$$\begin{aligned}
\text{COS}_{1,2} &= \frac{J_1 \cdot J_2}{\|J_1\| \|J_2\|} = \frac{\sum J_{1,i} \times J_{2,i}}{\sqrt{\sum J_{1,i}^2 \times \sum J_{2,i}^2}} \\
&= \frac{331 \times 9691 + 110 \times 0 + 0 \times 9959 + \dots}{\sqrt{(0^2 + 331^2 + 110^2 + 0^2 + \dots) \times (0^2 + 9691^2 + 0^2 + 9959^2 + \dots)}} \\
&= 0.0008
\end{aligned}$$

Correspondingly, the difficulty of making this combination is: $1 - \text{COS}_{1,2} = 0.9992$. We calculate the difficulty of all the other journal combinations following the same procedure. At the paper level, we sum up these difficulty scores and get a novelty measure, $\text{novelty} = 8.9891$, which places the paper in the top 1% of novel papers in its field.

Appendix II: Variables, descriptive statistics, and additional regressions

Table A1. List of variables

Variable	Description	
1	Novelty	Continuous combinatorial novelty score.
2	NOV CAT1	Novelty class dummy: 1 if non-novel, i.e., if a paper has no new journal combinations, and 0 otherwise.
3	NOV CAT2	Novelty class dummy: 1 if moderately novel, i.e., if a paper makes at least one new combination but has a novelty score lower than the top 1% of its subject category, and 0 otherwise.
4	NOV CAT3	Novelty class dummy: 1 if highly novel, i.e., if a paper has a novelty score among the top 1% of its subject category, and 0 otherwise.
5	Citations (14y)	Cumulative number of citations in a 14-year time window, i.e., 2001-2014.
6	Top 1% cited (14y)	Dummy, 1 if among the top 1% cited in the same subject category, based on 14-year citations.
7	Top 1% cited (3y)	Dummy, 1 if among the top 1% cited in the same subject category, based on 3-year citations.
8	Citing fields	The number of WoS subject categories citing the focal paper.
9	Ratio of foreign field citations	The proportion of citations that are from papers sharing no common WoS subject categories, using a 14-year citation time window.
10	Top 1% cited in home fields (14y)	Dummy, 1 if among the top 1% cited in the same subject category, based on 14-year home field citations, i.e., citations received from subsequent papers sharing at least one common WoS subject categories.
11	Top 1% cited in foreign fields (14y)	Dummy, 1 if among the top 1% cited in the same subject category, based on 14-year foreign field citations, i.e., citations received from subsequent papers sharing no common WoS subject categories.
12	Cited by big hits (9y)	Dummy: 1 if cited by a big hit published between 2001 and 2009. The citing big hits are identified as the top 1% highly cited article in the same WoS subject category and publication year, based on their cumulative citations till 2014. Only big hits published between 2001 and 2009 are identified, so that each citing article has at least six years to accumulate citations, for a reliable identification of citing big hit articles.
13	JIF	The Impact Factor of the journal where the focal paper is published in.
14	International	Dummy: 1 if internationally co-authored, and 0 otherwise.
15	Authors	The number of authors.
16	References	The number of references.

Table A2. Descriptive statistics and Spearman correlations

Variable	Mean	Std. Dev.	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 Novelty	0.25	1.26	0	249															
2 NOV CAT1	0.89	0.31	0	1	-1.00														
3 NOV CAT2	0.10	0.30	0	1	.93	-.95													
4 NOV CAT3	0.01	0.10	0	1	.32	-.29	-.03												
5 Citations (14y)	26.28	72.99	0	30068	.11	-.11	.10	.04											
6 Top 1% cited (14y)	0.01	0.10	0	1	.02	-.02	.02	.02	.17										
7 Top 1% cited (3y)	0.01	0.10	0	1	.01	-.01	.01	.01	.16	.46									
8 Citing fields	9.30	8.10	0	189	.15	-.15	.14	.06	.86	.15	.13								
9 Ratio of foreign field citations	0.46	0.30	0	1	.08	-.08	.07	.03	.07	.02	.01	.26							
10 Top 1% cited in home fields (14y)	0.01	0.10	0	1	.01	-.01	.01	.01	.17	.66	.40	.14	-.04						
11 Top 1% cited in foreign fields (14y)	0.01	0.10	0	1	.03	-.03	.02	.03	.17	.67	.38	.15	.07	.35					
12 Cited by big hits (9y)	0.13	0.33	0	1	.05	-.05	.04	.03	.43	.24	.20	.38	.04	.23	.22				
13 JIF	2.05	2.42	0	33	.04	-.04	.04	.01	.53	.08	.09	.47	.07	.08	.07	.24			
14 International	0.19	0.39	0	1	.01	-.01	.01	.01	.09	.02	.02	.06	.00	.02	.01	.04	.10		
15 Authors	4.10	6.18	1	743	.02	-.02	.02	.00	.21	.02	.04	.21	.08	.02	.02	.08	.28	.20	
16 References	28.47	18.04	1	631	.24	-.24	.21	.10	.39	.06	.06	.35	.07	.05	.06	.16	.32	.06	.02

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection.

Table A3. Direct and direct impact of novel research

	NOV CAT1	NOV CAT2	NOV CAT3
% being top 1% cited (14-year)	0.92%	1.52%	3.07%
Average citations of citing papers	1.10	1.94	2.54
Average JIF of citing papers	0.15	0.25	0.31
Probability of citing paper to be a top 1% paper (average annual '01-'09)	2.27%	3.22%	4.37%
Cited by big hits (9-year)	12.03%	16.63%	22.08%

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection.

Table A4. Transdisciplinary impact of novel research

	(1)	(2)	(3)	(4)	(5)	(6)
	# citing fields (14-year)	# citing fields (14-year)	# citing fields (14-year)	Ratio foreign field citations (14-year)	Ratio foreign field citations (14-year)	Ratio foreign field citations (14-year)
	Poisson	Poisson	Poisson	OLS	OLS	OLS
NOV CAT2	0.1005*** (0.0013)	0.0963*** (0.0013)	0.0979*** (0.0013)	0.0489*** (0.0009)	0.0530*** (0.0009)	0.0521*** (0.0009)
NOV CAT3	0.1656*** (0.0039)	0.1581*** (0.0039)	0.1611*** (0.0039)	0.0821*** (0.0025)	0.0902*** (0.0025)	0.0882*** (0.0025)
14-year citations (ln)	0.5548*** (0.0007)	0.5544*** (0.0007)	0.5550*** (0.0007)	0.0030*** (0.0003)	0.0038*** (0.0003)	0.0033*** (0.0003)
# own fields (ln)		0.1075*** (0.0010)			-0.1082*** (0.0006)	
# own fields > 1			0.0805*** (0.0010)			-0.0982*** (0.0006)
International	-0.0120*** (0.0011)	-0.0118*** (0.0011)	-0.0119*** (0.0011)	-0.0054*** (0.0007)	-0.0055*** (0.0007)	-0.0055*** (0.0007)
Authors (ln)	0.0022* (0.0009)	0.0010 (0.0009)	0.0017+ (0.0009)	0.0122*** (0.0005)	0.0144*** (0.0005)	0.0135*** (0.0005)
Refs (ln)	0.0107*** (0.0010)	0.0147*** (0.0010)	0.0126*** (0.0010)	0.0062*** (0.0005)	0.0022*** (0.0005)	0.0038*** (0.0005)
N	1056918	1056918	1056918	990479	990479	990479
Log lik	-2635145	-2624447	-2629356			
Chi2	1746164***	1757538***	1742435***			
R2				0.1276	0.1525	0.1481

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. # citing fields (column 1-3) is the number of WoS subject categories citing the focal paper. Ratio foreign field citations (column 4-6) is the proportion of all citations that are from papers sharing no common WoS subject categories with the focal cited paper. # own fields is the number of WoS subject categories that the focal paper itself is affiliated with. # own fields > 1 is a dummy variable, which takes 1 if the focal paper has more than 1 WoS subject categories and 0 if only one subject category. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** p<.001, ** p<.01, * p<.05, + p<.10.

Table A5. Big hits in home fields

	Top 1% cited (1y) logit	Top 1% cited (2y) Logit	Top 1% cited (3y) logit	Top 1% cited (4y) Logit	Top 1% cited (5y) logit	Top 1% cited (6y) logit	Top 1% cited (7y) logit	Top 1% cited (8y) logit	Top 1% cited (9y) logit	Top 1% cited (10y) logit	Top 1% cited (11y) logit	Top 1% cited (12y) logit	Top 1% cited (13y) logit	Top 1% cited (14y) logit
NOV	-0.3063***	-0.3728***	-0.3080***	-0.2689***	-0.2383***	-0.2224***	-0.2145***	-0.1917***	-0.1473***	-0.1152***	-0.1016**	-0.0879**	-0.0878**	-0.0837**
CAT2	(0.0423)	(0.0369)	(0.0343)	(0.0333)	(0.0327)	(0.0325)	(0.0321)	(0.0318)	(0.0314)	(0.0311)	(0.0309)	(0.0308)	(0.0308)	(0.0307)
NOV	-0.3301**	-0.4322***	-0.2748**	-0.1773*	-0.1592*	-0.0613	-0.0834	-0.0859	-0.0729	-0.0325	-0.0018	0.0230	0.0208	-0.0052
CAT3	(0.1105)	(0.0933)	(0.0811)	(0.0764)	(0.0751)	(0.0723)	(0.0725)	(0.0722)	(0.0720)	(0.0713)	(0.0705)	(0.0699)	(0.0700)	(0.0706)
International	0.1933***	0.1796***	0.1521***	0.1317***	0.1231***	0.1154***	0.1163***	0.1130***	0.1057***	0.1016***	0.0899***	0.0946***	0.0833**	0.0801**
al	(0.0294)	(0.0258)	(0.0246)	(0.0244)	(0.0242)	(0.0242)	(0.0241)	(0.0241)	(0.0241)	(0.0241)	(0.0242)	(0.0242)	(0.0242)	(0.0243)
Authors	0.4512***	0.6870***	0.7303***	0.7095***	0.6964***	0.6754***	0.6531***	0.6208***	0.6045***	0.5913***	0.5793***	0.5598***	0.5354***	0.5177***
(ln)	(0.0235)	(0.0200)	(0.0189)	(0.0186)	(0.0183)	(0.0182)	(0.0182)	(0.0182)	(0.0181)	(0.0181)	(0.0181)	(0.0182)	(0.0182)	(0.0183)
Refs (ln)	0.8235***	1.1614***	1.2466***	1.2647***	1.2622***	1.2557***	1.2537***	1.2653***	1.2546***	1.2308***	1.2164***	1.2151***	1.2081***	1.2136***
	(0.0246)	(0.0224)	(0.0216)	(0.0213)	(0.0210)	(0.0210)	(0.0208)	(0.0208)	(0.0207)	(0.0207)	(0.0207)	(0.0206)	(0.0206)	(0.0206)
N	1051487	1055028	1054548	1055870	1055870	1055765	1055768	1055875	1056146	1056146	1056041	1056041	1055980	1056146
Log lik	-39236	-47113	-50681	-51997	-52999	-53156	-53944	-54270	-54546	-54745	-54970	-55024	-55191	-55156
Chi2	2446***	4763***	5684***	5808***	5872***	5691***	5601***	5527***	5415***	5235***	5085***	5051***	4872***	4823***

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. Big hits are identified exclusively by home field citations, i.e., citations received from subsequent publications that share at least one common WoS subject category with the focal paper. Being a big hit in home fields using a t -year time window means among the top 1% highly cited papers within the same WoS subject category, based on their home field citations in the t -year time window starting from 2001. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** $p < .001$, ** $p < .01$, * $p < .05$, + $p < .10$.

Table A6. Big hits in foreign fields

	Top 1% cited (1y) logit	Top 1% cited (2y) Logit	Top 1% cited (3y) Logit	Top 1% cited (4y) logit	Top 1% cited (5y) logit	Top 1% cited (6y) logit	Top 1% cited (7y) logit	Top 1% cited (8y) logit	Top 1% cited (9y) logit	Top 1% cited (10y) logit	Top 1% cited (11y) logit	Top 1% cited (12y) logit	Top 1% cited (13y) logit	Top 1% cited (14y) logit
NOV	-0.1280**	-0.0072	0.0453	0.1482***	0.1808***	0.2162***	0.1967***	0.2387***	0.2554***	0.2703***	0.2853***	0.2779***	0.2766***	0.2939***
CAT2	(0.0417)	(0.0335)	(0.0311)	(0.0298)	(0.0289)	(0.0287)	(0.0288)	(0.0285)	(0.0282)	(0.0281)	(0.0280)	(0.0280)	(0.0280)	(0.0279)
NOV	-0.2961**	-0.0252	0.2839***	0.3919***	0.4671***	0.4672***	0.5384***	0.5722***	0.6074***	0.5884***	0.6444***	0.6316***	0.6269***	0.6237***
CAT3	(0.1125)	(0.0820)	(0.0666)	(0.0634)	(0.0599)	(0.0603)	(0.0582)	(0.0576)	(0.0565)	(0.0570)	(0.0559)	(0.0560)	(0.0560)	(0.0563)
International	0.2633***	0.2157***	0.1424***	0.0963***	0.0634**	0.0547*	0.14279+	0.0403	0.0309	0.0336	0.0379	0.0335	0.0467+	0.0600*
al	(0.0308)	(0.0261)	(0.0247)	(0.0247)	(0.0244)	(0.0245)	(0.0245)	(0.0245)	(0.0245)	(0.0245)	(0.0245)	(0.0245)	(0.0245)	(0.0245)
Authors	0.6596***	0.7648***	0.7878***	0.7672***	0.7483***	0.7383***	0.7086***	0.6729***	0.6529***	0.6181***	0.5926***	0.5794***	0.5597***	0.5436***
(ln)	(0.0220)	(0.0196)	(0.0187)	(0.0185)	(0.0182)	(0.0181)	(0.0181)	(0.0181)	(0.0180)	(0.0181)	(0.0181)	(0.0182)	(0.0183)	(0.0184)
Refs (ln)	0.9855***	1.1254***	1.1885***	1.1847***	1.2192***	1.1892***	1.1909***	1.1750***	1.1895***	1.1811***	1.1712***	1.1730***	1.1632***	1.1586***
	(0.0260)	(0.0231)	(0.0216)	(0.0213)	(0.0212)	(0.0211)	(0.0211)	(0.0211)	(0.0210)	(0.0209)	(0.0207)	(0.0207)	(0.0207)	(0.0208)
N	1044889	1054466	1055590	1055734	1055734	1056146	1056146	1055951	1056146	1056146	1056146	1055739	1056146	1056146
Log lik	-34166	-45431	-50380	-51412	-52954	-53222	-53781	-54143	-54439	-54548	-54819	-54783	-55003	-54878
Chi2	4099***	5415***	6332***	6468***	6669***	6430***	6371***	6140***	6185***	5945***	5887***	5732***	5615***	5518***

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. Big hits are identified exclusively by foreign field citations, i.e., citations received from subsequent publications that share no common WoS subject categories with the focal paper. Being a big hit in foreign fields using a t -year time window means among the top 1% highly cited papers within the same WoS subject category, based on their foreign field citations in the t -year time window starting from 2001. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** $p < .001$, ** $p < .01$, * $p < .05$, + $p < .10$.

Table A7. Big hits: novelty interact with JIF

	Top 1% cited (1y) logit	Top 1% cited (2y) Logit	Top 1% cited (3y) logit	Top 1% cited (4y) logit	Top 1% cited (5y) logit	Top 1% cited (6y) Logit	Top 1% cited (7y) logit	Top 1% cited (8y) logit	Top 1% cited (9y) logit	Top 1% cited (10y) logit	Top 1% cited (11y) logit	Top 1% cited (12y) Logit	Top 1% cited (13y) logit	Top 1% cited (14y) logit
NOV	-0.1436**	0.0021	0.0765	0.1255**	0.2129***	0.2310***	0.2382***	0.2540***	0.2993***	0.3354***	0.3315***	0.3068***	0.3502***	0.3417***
CAT2	(0.0550)	(0.0495)	(0.0479)	(0.0463)	(0.0443)	(0.0435)	(0.0429)	(0.0423)	(0.0412)	(0.0406)	(0.0403)	(0.0403)	(0.0396)	(0.0394)
NOV	-0.1364	0.1931+	0.4661***	0.6375***	0.6671***	0.6769***	0.7210***	0.7068***	0.7489***	0.7463***	0.7449***	0.7654***	0.7781***	0.7867***
CAT3	(0.1438)	(0.1138)	(0.0989)	(0.0899)	(0.0877)	(0.0859)	(0.0837)	(0.0836)	(0.0814)	(0.0814)	(0.0807)	(0.0793)	(0.0787)	(0.0779)
JIF	1.5661***	1.9481***	2.0416***	2.0346***	2.0388***	1.9851***	1.9432***	1.9035***	1.8743***	1.8537***	1.8140***	1.7846***	1.7683***	1.7338***
TOP10%	(0.0274)	(0.0252)	(0.0249)	(0.0247)	(0.0245)	(0.0243)	(0.0242)	(0.0241)	(0.0240)	(0.0240)	(0.0239)	(0.0238)	(0.0239)	(0.0238)
JIF	-0.1441+	-0.2263**	-0.2189***	-0.2386***	-0.3294***	-0.3228***	-0.3052***	-0.2834***	-0.3278***	-0.3437***	-0.3232***	-0.3016***	-0.3411***	-0.3414***
TOP10% *	(0.0780)	(0.0658)	(0.0626)	(0.0609)	(0.0592)	(0.0584)	(0.0579)	(0.0573)	(0.0568)	(0.0563)	(0.0561)	(0.0563)	(0.0558)	(0.0560)
NOV														
CAT2														
JIF	-0.2052	-0.5628**	-0.6241***	-0.6226***	-0.6392***	-0.5684***	-0.5894***	-0.5909***	-0.5779***	-0.5627***	-0.5374***	-0.5791***	-0.5816***	-0.5169***
TOP10% *	(0.2072)	(0.1631)	(0.1409)	(0.1288)	(0.1262)	(0.1233)	(0.1219)	(0.1228)	(0.1203)	(0.1204)	(0.1197)	(0.1196)	(0.1193)	(0.1172)
NOV														
CAT3														
Internation	0.1901***	0.1488***	0.0907***	0.0707**	0.0535*	0.0586*	0.0554*	0.0489*	0.0515*	0.0543*	0.0484*	0.0289	0.0216	0.0312
al	(0.0280)	(0.0246)	(0.0241)	(0.0240)	(0.0238)	(0.0238)	(0.0239)	(0.0239)	(0.0239)	(0.0239)	(0.0240)	(0.0241)	(0.0241)	(0.0241)
Authors	0.4802***	0.6222***	0.6751***	0.6507***	0.6193***	0.6033***	0.5813***	0.5501***	0.5190***	0.4942***	0.4737***	0.4481***	0.4366***	0.4167***
(ln)	(0.0216)	(0.0199)	(0.0195)	(0.0193)	(0.0190)	(0.0189)	(0.0188)	(0.0188)	(0.0188)	(0.0188)	(0.0189)	(0.0189)	(0.0189)	(0.0190)
Refs (ln)	0.7393***	0.9478***	0.9939***	1.0154***	1.0211***	1.0235***	1.0117***	0.9960***	0.9924***	0.9846***	0.9803***	0.9821***	0.9806***	0.9715***
	(0.0257)	(0.0242)	(0.0239)	(0.0237)	(0.0232)	(0.0231)	(0.0230)	(0.0229)	(0.0228)	(0.0228)	(0.0227)	(0.0227)	(0.0227)	(0.0225)
N	1052801	1055915	1056516	1056757	1056778	1056574	1056703	1056803	1056895	1056781	1056813	1056902	1056895	1056929
Log lik	-39508	-46753	-48568	-49580	-50638	-51165	-51537	-51998	-52395	-52481	-52831	-53062	-53209	-53472
Chi2	8514***	14380***	16198***	16406***	16649***	16089***	15574***	15093***	14746***	14305***	13933***	13624***	13310***	12999***

Data consist of all WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection. Big hits are identified based on all citations (i.e., both home and foreign field citations). Being a big hit in a t -year time window means among the top 1% highly cited papers within the same WoS subject category and publication year, based on their citations in the t -year time window starting from 2001. Field (WoS subject category) fixed effects incorporated. Robust standard errors in parentheses. *** $p < .001$, ** $p < .01$, * $p < .05$, + $p < .10$.

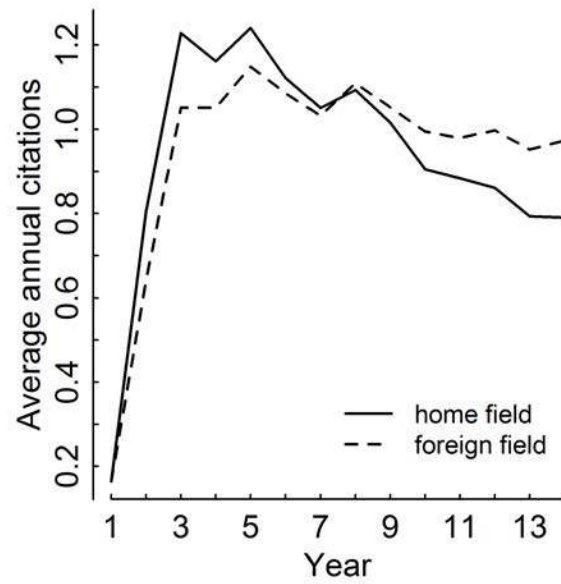


Figure A1. Average annual citations. The average number of annual citations over time, separating home and foreign fields. Data consist of 1,056,936 WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection.

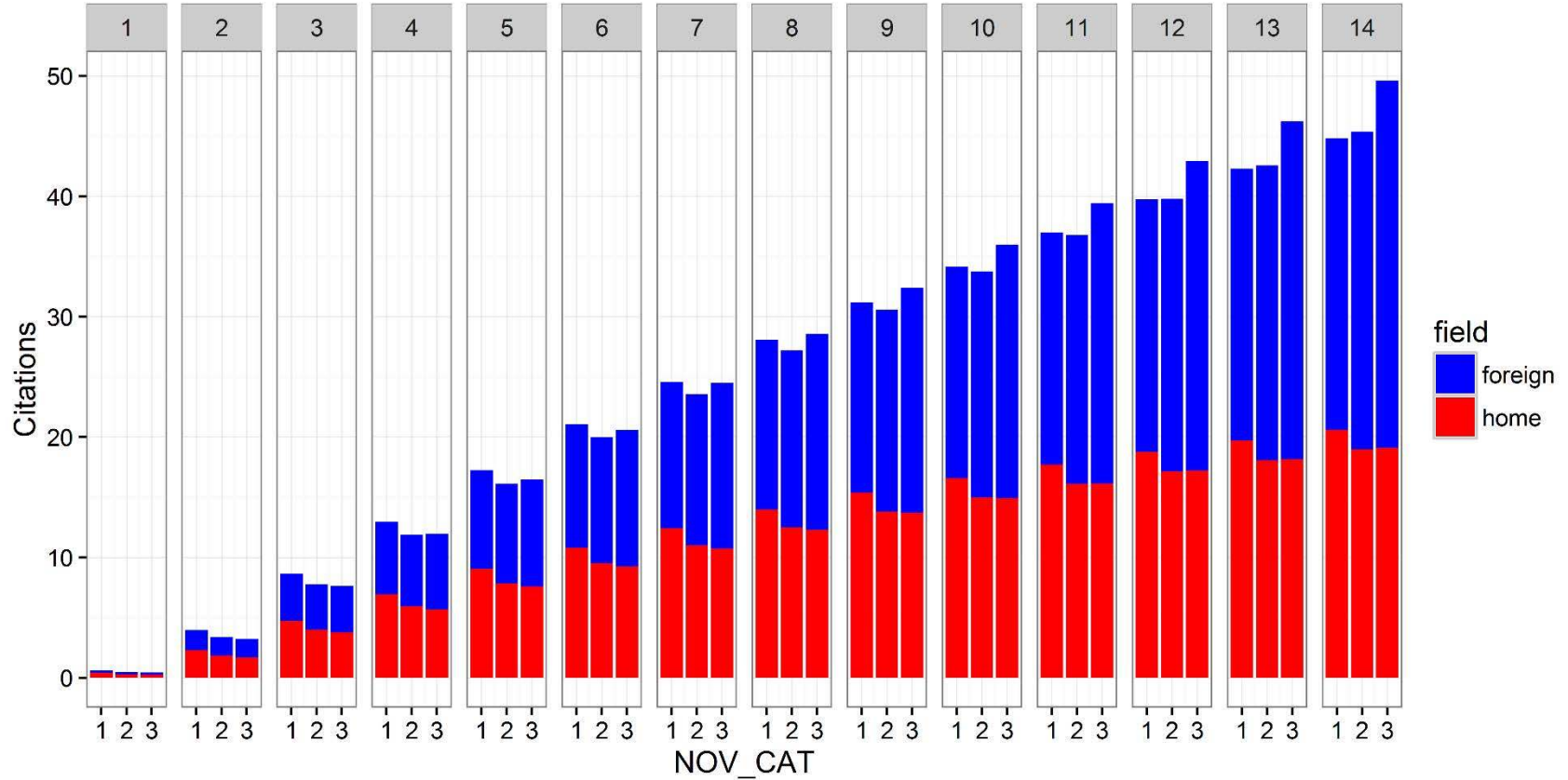


Figure A2. Estimated cumulative number of citations by novelty classes and time windows, separating home and foreign field citations. Estimates are based on a set of Poisson regressions. Using negative binomial models yields similar results. Data consist of 1,056,936 WoS articles published in 2001 and are sourced from Thomson Reuters Web of Science Core Collection.

Appendix III: Robustness analysis

In summary, we find that novel papers have (1) a higher dispersion in citations, (2) a higher chance of being a big hit in the long term, (3) a higher chance of being cited by big hits, (4) a broader impact across scientific fields, (5) a larger share of citations from foreign fields, (6) not a higher chance of being highly cited in home field, (7) a higher chance of being highly cited in foreign field, (8) a lower chance of being a big hit in the short term, and (9) are published in journals with lower Impact Factors. In this section we test the robustness of these nine findings.

III.1. Scientific field heterogeneity

Although we control for scientific field effects, and some of our measures for novelty (i.e., highly novel) and impact (e.g., big hits) are field specific, it is nevertheless possible that the relationship between novelty and impact is field specific. To test this possibility, we examine whether our main findings are robust across scientific fields, replicating the whole set of analyses separately by field. We use four groups: AH (Arts and Humanities), LS (Life Sciences), PSE (Physical Sciences and Engineering), and SS (Social Sciences). We also distinguish between LS2 (Medicine) and the rest (LS1) within LS and distinguish between PSE2 (Computer Sciences; Engineering) and the rest (PSE1) within PSE. Both LS2 and PSE2 are the more applied counterparts of LS1 and PSE1. In total, we run separate regressions for the following eight groups: AH, LS, LS1, LS2, PSE, PSE1, PSE2, and SS. While our findings are robust for LS and PSE fields, they are less robust for AH and SS fields. Specifically, findings, (1) higher dispersion, (8) fewer short-term big hits, and (9) lower JIF for novel papers, are not robust for AH, and finding (1) higher dispersion is not robust for SS. This may suggest that the relationship between novelty and impact varies across fields and our findings hold most specifically for hard sciences and engineering. However, it may also be an artifact of data limitations. The WoS coverage for humanities and social sciences is much smaller than hard sciences, so we have much fewer observations for AH and SS than for the hard sciences. More importantly, because of this coverage issue, using the WoS data does not capture sufficiently all the publishing and referencing transactions in humanities and social sciences (Hicks, 2004), which is required for constructing measures of novelty and impact.

III.2. Novelty measure variations

First, we test whether our findings hold when we use alternative formulas for our novelty measure. As explained in section 3.1, our novelty measure is essentially the number of new referenced journal pairs, weighted by the distance between the newly paired journals (i.e., *weighted sum*). Alternatively we can use the novelty score of the most distinct pair among all the new pairs (i.e., *max score*) or the proportion of all journal pairs that are new, weighted by the distance (i.e., *weighted share*).

The maximum novelty score,

$$Novelty_{max\ score} = \max_{J_i-J_j\ pair\ is\ new} (1 - COS_{i,j})$$

focuses exclusively on the novelty score of the most distant new journal pair instead of mixing both the number and the difficulty of new journal pairs. We find using the *max score* approach that all our findings hold, except finding 6, specifically, while *max score CAT2* also has a significantly negative effect on being highly cited in the home field, *max score CAT3* has a small but significantly ($p = 0.09$) positive effect. One possible explanation is that papers with a small number of very distant new combinations but at same time a large number of conventional combinations within the home field are likely to score high on the *max score* measure, and the large number of home field combinations makes the paper more likely to be accepted by the home field. For a further assessment we compare the size of the effect. Highly novel defined by *max score*, compared with defined by *weighted sum*, has a larger effect on the likelihood of being a long-term big hit (i.e., finding 2) but smaller effects for all other findings, i.e., all nine findings except 2 and 6. We conclude that our *weighted sum* approach captures at least more of the “high risk”, if not also the “high gain,” nature of novel research.

Because of the concern that our *weighted sum* measure of novelty might be over-dependent on the number of references in the focal paper, which including the number of references in the regression analysis may not sufficiently control for, we also inspect the *weighted share* approach, which essentially normalizes our novelty measure for the number of journal pairs. It can also be

viewed as a reversed and weighted *network density*⁹ measure with the number of missing ties (i.e., new ties which did not exist in previous years, weighted by the distance) in the numerator and the size of the network (i.e., the number of all journal pairs regardless new or not) in the denominator. Specifically,

$$Novelty_{weighted\ share} = \frac{1}{n} \sum_{J_i-J_j\ pair\ is\ new} (1 - COS_{i,j})$$

where n is the number of all co-cited journal pairs. All findings hold using this *weighted share* approach. In terms of the size of the effect, highly novel defined by *weighted share*, compared with defined by *weighted sum*, has larger effects on finding 8 (i.e., fewer short-term big hits) and on finding 9 (i.e., lower JIF) but smaller effects for all other findings. The *weighted share* measure imposes a penalty on papers with a large number of referenced journals, in other words, papers with a larger network of referenced journals. We believe that network size is also an important aspect of combinatorial novelty and therefore should not be eliminated from the analysis. Specifically, a larger network making the same number of new connections should not be evaluated as less novel than a smaller network. Furthermore, the *weighted share* measure is very sensitive when a paper has very limited number of referenced journals. Therefore, we prefer our *weight sum* measure to the *weighted share* approach.

Second, our novelty indicator used in the analysis excluded the 50% least cited journals and required reuse of the new combination in the next three years. To check the sensitivity of the analysis to these choices, we replicate the analysis without these restrictions. In addition, although most new journals are already excluded in the analysis because they are typically among the lower cited journals, we also checked the results excluding new journals from the calculation of *novelty*. Moreover, Boyack and Klavans (2014) warned that the *atypicality* measure in Uzzi et al. (2013) is confounded with citing star journals, such as *Science* and *Nature*. Our novelty measure is unlikely to be confounded with citing star journals, which are so highly cited that combining them with any other journals is very unlikely to be new. Nevertheless, we check results excluding the top 10% highly cited journals, as well as

⁹ Network density is the proportion of all possible ties that are actually present in the network.

multidisciplinary journals. In summary, we test robustness of our findings using the following variations of the *novelty* measure: (a) no restrictions, (b) only exclude the 50% least cited journals, (c) only require reuse in 3 years, (d) only exclude new journals, (e) exclude the 50% least cited journals, require reuse in 3 years, and exclude the 10% top cited journals, and (f) exclude the 50% least cited journals, require reuse in 3 years, and exclude the 10% top cited and multidisciplinary journals. Our findings are robust using all these alternative specifications.

Third, to accommodate the skewness of the indicator, we created three novelty categories. When we duplicate the results using the natural logarithm transformed continuous novelty score in the regression, all results are robust.

Fourth, we classified highly novel papers as the top 1% novel papers in the same subject category. We also use different thresholds for the categorization, specifically, classifying the top 5% or 0.1% papers as highly novel. All results are robust, and the changes in effect size are consistent with what we would expect from comparing the coefficients on highly and moderately novel classes in our reported results. For example, compared with our reported results for classifying the top 1% papers as highly novel, highly novel would have a larger effect on the likelihood of big hits when classifying top 0.1% papers as highly novel but a smaller effect when classifying top 5% papers as highly novel.

III.3. Novelty versus atypicality

We compare our novelty indicator with the Uzzi et al. (2013) measure of *atypicality*. For a scientific publication, Uzzi et al. (2013) calculated the commonness score for all its referenced journal pairs, where the commonness score is a z -score, (i.e. the number of observed co-citations between the pair – the number of expected co-citations) / standard deviation of the co-citations) and labelled the lowest 10th percentile of this series of commonness scores as their indicator of novelty. To distinguish it from our measure of novelty, we label their indicator as *atypicality*. Lee et al. (2015) used an adapted version in their study. Specifically, they used the ratio between the number of observed co-citations and the number of expected co-citations as the commonness score of a journal pair, instead of the z -score. In addition, they take the natural logarithm of the commonness score and add a negative sign, obtaining a roughly normally distributed variable positively associated with *atypicality*, while the commonness score is negatively associated with

atypicality. Here we follow this adapted version to calculate the Uzzi et al. (2013) indicator for our sampled papers. To make the comparison, we categorize the continuous *atypicality* indicator into three classes with the same proportion of papers in each of the three classes, specifically, *ATP CAT* = 3 if top 1% in the same WoS subject category and publication year, 2 if below top 1% but above top 10%, and 1 for all others. In addition, we also compare the continuous versions of both *atypicality* and our *novelty* scores. Specifically, we assess results of six sets of regressions using the following independent variables: (a) *novelty* categories (*NOV CAT*), i.e., main results reported in the text, (b) *atypicality* categories (*ATP CAT*), (c) *NOV CAT* and *ATP CAT* together, (d) *novelty* score, (e) *atypicality* score, (f) *novelty* and *atypicality* scores together.

We focus on two criteria for assessing the results: the size of the effect and the consistency of the results across these six settings. When both categorical *novelty* and *atypicality* are in the regression, i.e., in setting (c), all effects of *novelty* (i.e., *NOV CAT2* and *NOV CAT3* on findings 1-9) remain consistent. *Atypicality* classes, compared with *novelty* classes, have smaller and insignificant effects on (1) higher dispersion and (8) fewer short-term big hits; smaller but significant effect on (3) higher indirect impact; larger effect on (2) more long-term big hits and (4) broader impact, (5) higher share of foreign field citations, (6) fewer big hits in home field, and (7) more big hits in foreign field; and reversed effect on (9) low JIF¹⁰. When having both continuous *novelty* and *atypicality* scores in the regressions, i.e., in setting (f), again all the effects of *novelty* remain consistent, while the *atypicality* score, compared with the *novelty* score, has reversed but insignificant effect on (1) higher dispersion; reversed and significant effect on (8) fewer short-term big hits and (9) lower JIF; smaller and insignificant effect on (6) fewer big hits in home field; smaller and significant effect on (3) higher indirect impact; and larger effect on (2) more long-term big hits, (4) broader impact, (5) higher share of foreign field citations, and (7) more big hits in foreign field. Based on the comparison of effect size, it seems that our *novelty* indicator better captures the “high risk” nature of novel research than does the *atypicality* score. In terms of “high gain,” *atypicality* better captures the higher direct impact and broader impact, while *novelty* better captures the indirect impact of stimulating follow-on breakthroughs.

¹⁰ Specifically, *ATP CAT2* has a positive and significant effect, while *ATP CAT3* has a positive but insignificant effect on JIF.

In terms of consistency across these six settings, our *novelty* measure has considerably more reliable and robust behavior than *atypicality*. While effects of our *novelty* measure are robust across all six settings, the results of *atypicality* are not consistent across settings. For example, *ATP CAT3* has a significantly negative effect on short-term big hits, but *atypicality* score has a significantly positive effect; *atypicality* has a significantly negative effect on JIF in setting (b) but a positive effect in other settings; and *atypicality* has a significantly negative effect on big hits in home field when treated alone in setting (e) but an insignificantly negative effect when treated together with novelty in setting (f). Overall, we conclude that our *novelty* indicator behaves more reliably, captures more the “high risk” nature of novel research, and measures aspects of research not captured by the *atypicality* measure.