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Hypoallometric scaling in international collaborations

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HIGHLIGHTS

- Globally, multinational collaboration scales sublinearly with gross scholarly output.
- Hypoallometric scaling of international collaboration is temporally conserved.
- Organizational constraints likely contribute to declining rates of international collaboration.

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ABSTRACT

Collaboration is a vital process and dominant theme in knowledge production, although the effectiveness of policies directed at promoting multinational research remains ambiguous. We examined approximately 24 million research articles published over four decades and demonstrated that the scaling of international publications to research productivity for each country obeys a universal and conserved sublinear power law. Inefficient mechanisms in transborder team dynamics or organization as well as increasing opportunity costs may contribute to the disproportionate growth of international collaboration rates with increasing productivity among nations. Given the constrained growth of international relationships, our findings advocate a greater emphasis on the qualitative aspects of collaborations, such as with whom partnerships are forged, particularly when assessing research and policy outcomes.

1. Introduction

Research teams are the dominant producers of knowledge and high impact work across multiple scientific disciplines [1]. Although team size is customarily defined by the number of authors, recent studies indicate that having multiple institutional and state level affiliations is also associated with greater citations and is becoming more prevalent in publications [2,3]. Tangible advantages of large international networks have likely fueled the widespread inclusion of team oriented investigations in the research portfolios of governments and funding agencies. Notable examples include comprehensive DNA sequencing efforts in biomedical research and massive particle physics experiments involving labs and experts throughout the world. Indeed, the emergence of international collaborations over the last several decades across many disciplines has been enumerated in previous studies [3–8]. A recent study further suggests that the growth of international science may be attributed in part to the greater integration of developing countries into the global research network [9]. However, the impact of national policies and funding programs that champion multinational research remains

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ambiguous if not inconsequential, suggesting that the drivers and assembly mechanisms of international teams remain to be elucidated [10]. In addition, barriers and detriments of multinational collaborative practices remain poorly characterized despite their potential widespread impact in academia and obvious policy implications in the promotion of multinational science teams [11].

Allometric relationships describing the rate of growth in organism traits relative to body size are omnipresent in physiology and are characterized by defined scaling constants. For instance, the three-quarter or two-thirds power relation between metabolism and organism mass demonstrating that energy consumption grows more slowly than the whole body has been illuminated in great detail across species in both animals and plants [12–17]. Other biological measurements that obey power law scaling include lifespan, heart rate, tree heights, aorta lengths, and sleep cycle time [13,18]. Remarkably, social indicators, such as the growth of companies and universities and urban measures of cities including innovation, economic activity, and crime, also exhibit allometric behaviors [19–21]. While the predictable design of many natural processes based on simple power laws is intriguing, it is also of functional importance. In particular, the ubiquitous governance of growth by power exponents in various systems is suggestive of generic mechanisms which has led to several empirically supported principles of allometry in biological and social dynamics [12,15,17,22–25]. For example, the sublinear scaling of cellular metabolism in many metazoan species is theorized to be attributed to space-filling hierarchical networks [15]. Such distribution networks encompassing vascular or circulatory systems are necessary to overcome geometric constraints to life by maintaining an appropriate surface area to volume ratio of cells and entire organisms.

Herein, we assessed nation-level production of primary research publications by solo authors and domestic and international collaboratives across the world and spanning the natural, applied, and social disciplines. Our results demonstrate that each mode of scholarship scales with total productivity (defined as gross paper output) raised to a unique scaling exponent: scientific research stemming from international teams obeys a sublinear (scaling exponent less than one) scaling law while domestic team and solo author works conform to linear (scaling exponent equal to one) and superlinear (scaling exponent greater than one) scaling laws, respectively. We theorize that growth of international collaborations among nations is not merely stochastic but likely bounded by structural or functional limits, such as diseconomies of scale. Our findings potentially clarify why considerable efforts to foster greater transborder endeavors have not transpired into measurable success [10].

2. Methods

We analyzed all primary research articles in the Thomson Reuters Web of Science (WOS) database that were published between 1973 and 2009. Our study was restricted to English language papers defined as articles or conference proceedings. Articles were separated into distinct subject disciplines by their WOS category fields: technology and engineering, physical science, life science, social science, and arts and humanities. Our WOS dataset was composed of 24,161,726 articles, with 2,838,004 papers in technology and engineering, 7,479,363 papers in the physical sciences, 12,199,030 papers in the life sciences, 1,225,686 papers in the social sciences, and 419,643 papers in the arts. In 2009 alone, 1,374,963 English primary research articles were published across all subjects. Country affiliations from among 197 nations (including Taiwan and Hong Kong given their largely autonomous governance) were determined from author address and reprint address field tags. Individual nations were utilized as the unit of analysis in analyzing scaling relationships for a specific year.

To assess collocation of authors, information which could not be derived from the WOS database including author specific institutional affiliations and national affiliations were curated by manual inspection of 4709 primary research articles published in 2013 in the following journals: *Cell*, *Cancer Cell*, *Nature Cell Biology*, *Journal of Clinical Investigation*, *PLOS Biology*, *Nature Structural and Molecular Biology*, *Genes and Development*, *Journal of Cell Biology*, *EMBO*, *Cell Death and Differentiation*, *EMBO Reports*, *Journal of Cell Science*, *BMC Biology*, *International Journal of Biochemistry and Cell Biology*, *Journal of Cellular Physiology*, *FEBS Letters*, *Journal of Cellular Biochemistry*, *BMC Cell Biology*, *Molecular Biology Reports*, *Molecular and Cellular Biochemistry*, and *Cell Biochemistry and Function*. Journals were restricted to the cellular and molecular biology disciplines and selected to provide a range of impact factors. Additionally, we sought to include only journals that published at least 80 publications in 2013 and had no more 70% of all publications affiliated with a single nation.

3. Results

In order to characterize the intensification of international collaborations in research, we analyzed all primary articles published in the physical, life, engineering, social, and arts disciplines between 1973 and 2009 in the Thomson Reuters Web of Science database. International collaborations were defined by the presence of more than one national affiliation in a publication. While international collaboratives were rare in the 1970s, by the 2000s they contributed to an enlarging and sizable proportion of published works (see Fig. S1(a) in supplemental material [26], Appendix A). When we assessed country-level publication and collaboration trends, we found a time unvarying discrepancy in the localization of high levels of gross publications or international publications and the ratio of international collaborations to total output, hereafter referred to as fractionalcollaborative output (Fig. 1 and see Fig. S1(b) in supplemental material [26], Appendix A). This finding indicates a global inverse relationship between research productivity and the proportion of research efforts invested in multinational teams, with countries such as the US and China displaying the highest relative levels of domestic collaborations worldwide (Fig. 1(b)).

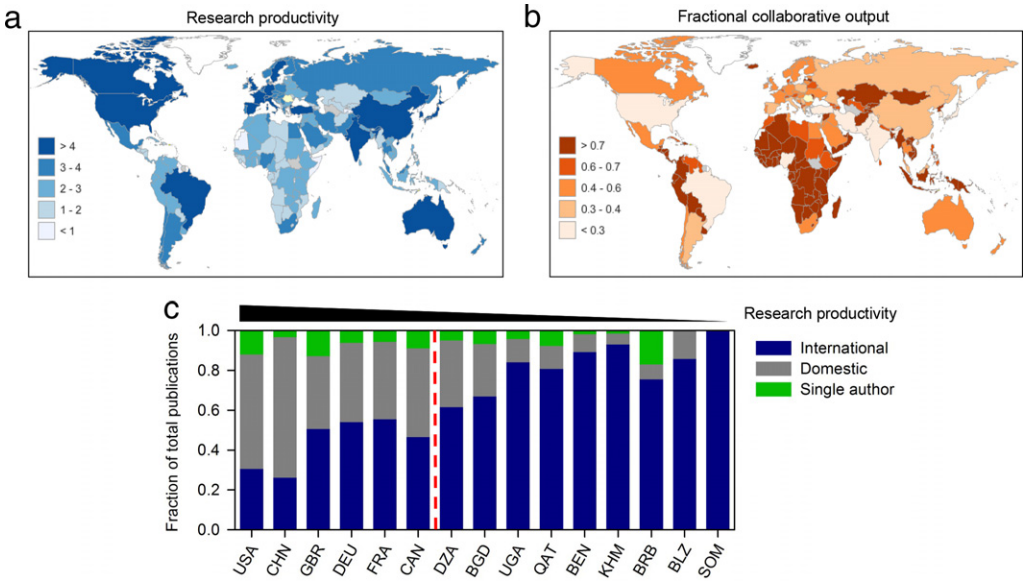

Fig. 1. An inverse relation between total research output and proportion of research efforts invested in multinational teams worldwide. Nation-level measures from 2009 of log-transformed total papers published (a) and fractional collaborative output (b) are shown across the globe. Dark and light colors denote the highest and lowest level of each measure, respectively. Maps were created with the StatPlanet software (http://www.statsilk.com/software/statplanet). (c) The fraction of international collaborations, domestic collaborations, and single author works contributing to the total research output of multiple countries is displayed. The red dotted line separates high and low research output countries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We next examined growth curves of different publication types including international collaborations, domestic collaborations (defined by publications with at least two authors and only having a single country affiliation) and single author papers. Of note, we apply the term "growth" in the context of scaling to refer to shifts in the productivity of countries among its peers rather than over time. Based on 2009 data from nearly every nation as seen in Fig. 2(a)–(c), all modes of scholarship followed a power law scaling function in relation to total research output. Other curve forms were considered such as an exponential function, though none provided a systematic improvement in the coefficient of determination. Notably, each type of scholarship could be discriminated by a scaling exponent (β) less than one (hypoallometric), greater than one, or equal to one. As reported by Bettencourt et al., distinguishing power law functions by their exponent provides crucial insight into temporal growth behaviors regulated by the availability and consumption of resources [27]. Thus, with $\beta < 1$, as seen in the scaling of international collaborations, temporal growth rates follow a sigmoid curve and eventually plateau over time at a defined carrying capacity. For $\beta = 1$ or >1, as seen in the scaling of domestic collaborations and single author papers, temporal growth rates follow an exponential or faster than exponential function, respectively. Remarkably, hypoallometric scaling of international collaborations (using data from 2009) was also observed with R&D expenditure ($\beta = 0.61, R^2 = 0.87, n = 57$), and number of researchers ($\beta = 0.78, R^2 = 0.49, n = 42$), indicating a preserved scaling property of international collaborations with other proxies of a nation's scientific or artistic productivity. Collectively, our findings denote the predictable growth of international collaborations. In addition, our results demonstrate that the sublinear scaling of international collaborations not only occurs over many orders of magnitude, but is also globally consistent, conserved over time, and present in all subject fields (Fig. 2(a)–(c) and see Fig. S2 in supplemental material [26], Appendix A).

International collaborations may be subject to diseconomies of scale akin to evolutionary or physical restraints due to cumbersome bureaucracy, complicated team dynamics, inadequate communication channels, and disorganized resource management. In support of this hypothesis, we manually examined nearly 4700 biomedical articles, published across 21 journals selected to provide a broad range of impact factors, on authorship structures not captured by the Web of Science. We found that the ratio of authors to geographically discrete institutes is higher in domestic collaborations compared to international collaborations, which cannot be attributed to differences in team sizes (Fig. 2(d) and see Fig. S3 in supplemental material [26], Appendix A). Thus, multinational team members are spread out over more administrative units analogous to top-heavy management structures and have reduced collocation, postulated to result in less vigorous or impactful relations [28].

Although the sublinear scaling of international collaborations has persisted over the last four decades, there was a perceptible increase in β over time. We plotted power law coefficients versus research output from data obtained over the last four decades which displayed a curve best fitted by an exponential rise to a maximum value function (Fig. 2(e)). This indicates that while β of international collaborations has increased over time, it is destined to remain less than one.

While the primary focus of this work was on international partnerships, it is notable that domestic collaborations scale linearly with total research production, denoting the continued dominance of domestic collaborations in knowledge creation

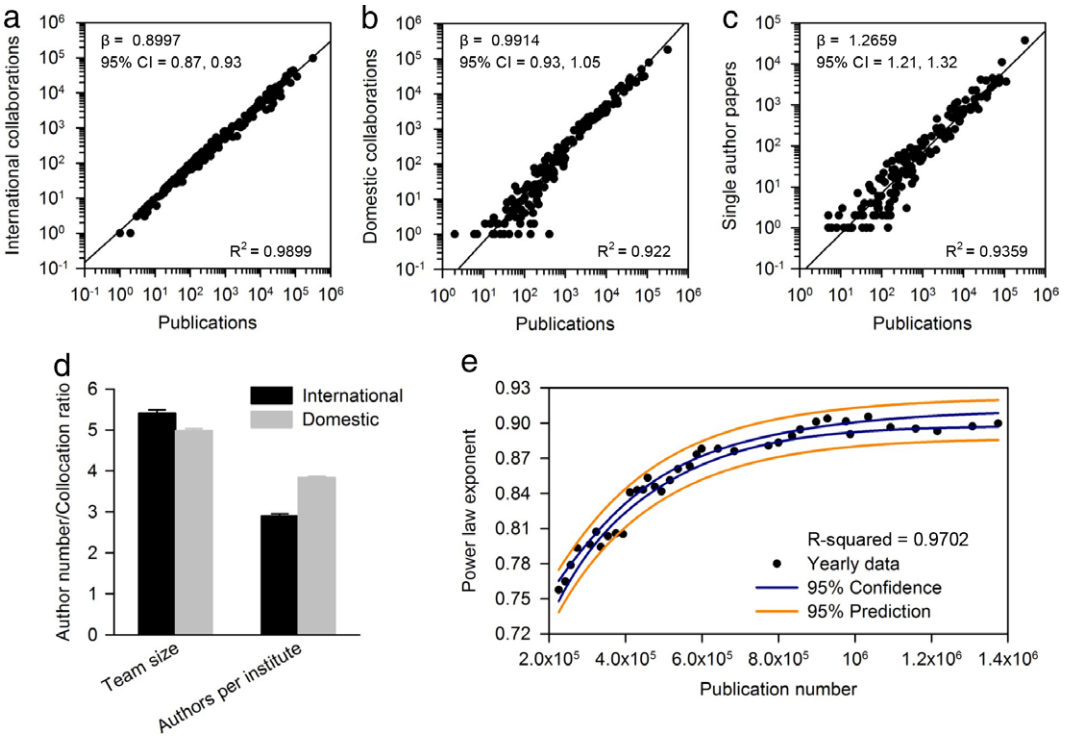

Fig. 2. Power laws are observed in the growth of distinct publication types. International collaborations (a), domestic collaborations (b), and single author papers (c) follow a sublinear, linear, and superlinear power law, respectively. The best-fit scaling relation is denoted by the solid line. Each data point represents the output of a country in 2009. (d) Average team sizes and ratios of authors per institute were calculated for international and domestic collaborations. Institutes in each publication were parsimoniously defined so that each author could only be assigned to one institute and the total number of institutes was minimized. (e) An exponential growth to maximum model of scaling exponents for international collaborations based on yearly data from 1973 to 2009. Of note, the upper 95% prediction interval indicates that β is bounded by an upper limit of approximately 0.92.

despite the rapid rise of international collaborations in recent years (Fig. 2(b)). Surprisingly, the growth of single author works obeys a superlinear scaling law often seen in social innovation and wealth creation, which diverges from earlier findings indicating a diminishing role of soloists in research (Fig. 2(c)) [1].

4. Discussion

Scaling laws offer powerful insights into the keyregulators of organizational structure and function during growth, as previously ascertained in multiple contexts [13,25]. In particular, hypoallometry has been linked to pervasive growth constraints within biological and other natural systems. For example, the decreased metabolic efficiency of metazoans (displaying sublinear scaling) compared to single cell prokaryotes and protists (displaying at least linear scaling) has been hypothesized to be attributed to the greater operational costs of dedicated vascular systems and other supportive tissue required of larger multicellular organisms for adequate material uptake and diffusion [29]. In plants, hypoallometric respiration rates are only observed among larger and mature plants while seedling and sapling metabolism scales linearly likely due to negligible effects of gravity on fluid mechanics at diminutive sizes [30]. Urban indicators also express distinct types of scaling behavior, with road surface, electric cables, and other infrastructure networks governed by efficiency demonstrating a slowing pace of growth with increasing city size [20]. A recent study has even demonstrated sublinear power law scaling of vocabulary size with corpus size attributed to the decreasing marginal need for new words [31]. In this work, we highlight how hypoallometric growth describes the growth of international collaboration. The distinction between sublinear versus linear and superlinear scaling suggests that international collaboratives face unique or greater restraints to growth, such as in organizational structures, compared to other modes of scholarly output. The larger power law exponent characteristic of growth in solo author works compared to domestic collaborations is also consistent with the idea that superlinear scaling originates from increased efficiency or decreased organizational costs. Intriguingly, the conformity of scientific output among nations to a universal scaling law despite their geographic, social, economic, and political differences suggests that research output and collaboration patterns are not idiosyncratic traits.

The mechanisms responsible for hypoallometry in multinational research remain to be elucidated. While physical distance is known to have an inhibitory effect on the likelihood of establishing collaborative ties, we hypothesize that diseconomies of scale in organizing ventures across borders, stemming from multiple factors including collocation, are considerable barriers to international science that have yet to be fully appreciated [3,32]. Opportunity costs, encompassing

the value of alternative choices forgone, of collaborating internationally versus domestically may also be greater in more scientifically developed countries. For example, if collaborations are a means of obtaining resources or expertise, it would be valuable for less scientifically developed countries to collaborate internationally. However, in developed countries with sufficient internal resources and experts, collaborating internationally may not be necessary or beneficial, and possibly at a cost. On the same note, opportunity costs may be least for less scientifically developed countries where a lack of internal resources or expertise may make collaborating domestically more prohibitive than finding research partners abroad.

Studies utilizing other bibliometric databases, examining non-English publications, or, in the case of assessing collocation, incorporating non-biomedical disciplines would help clarify whether our results are generalizable. Curiously, general mechanisms of research team assembly such as the formation of core teams and extended teams by Poisson processes and cumulative advantage ("preferential attachment") appear equivalent or comparable between domestic and multinational research publications [8,33–35]. This suggests that obstructive or inefficient mechanisms contributing to sublinear growth in international collaboratives may predominate at the level of institutes, regions, or nations rather than at the level of individual investigators. Nonetheless, distinguishing whether collocation or other putative mechanisms are causal or an effect of sublinear scaling in international collaborations remains to be determined.

The temporal shift of β possibly implies an evolution in the infrastructure of the modern research enterprise, which may be due to technological advancements, and changes in research practices or the nature of the science currently conducted. But the persistent sublinear scaling of international collaborations corroborates the inevitable relative decline in the ability of scientifically developing nations to contribute towards multinational research. Taken together, these results suggest that constraints to international collaboration have lessened over time, and are applicable to the collaborating capacity of the global research network and not just individual nations.

An alternate explanation of our findings is simply that transborder research occurs stochastically and that the decline in relative rates of international collaborations among high research production countries is due to numerical limitations, i.e. country A, which produces a hundred publications yearly, is unable to invest more than ten percent of its scientific output in multinational research because country B only produces ten publications yearly. However, several lines of evidence challenge this hypothesis: (1) Scaling constants remain unchanged by removing outlying nations that do not have close peers in terms of research productivity (namely the United States) and would thus represent countries that could possibly face numeric limits to international collaboration. (2) A size-independent stochastic process would not explain the universal tendency of low research output countries to collaborate internationally at an extremely high rate (in some cases nearly a hundred percent). (3) If collaborations among nations were driven by probabilities based on available capacity, scaling exponents would be expected to remain static as the global research network grows because power laws are scale invariant. Instead, as observed in Fig. 2(e), the scaling exponent of international collaborations varies with the magnitude of global research productivity while remaining consistently sublinear. (4) And lastly, a stochastic process would not explain or provide a mechanistic basis for distinct scaling exponents among different modes of scholarship.

Though the underlying mechanism requires further investigation, the sublinear scaling behavior of international collaborations helps illuminate why even directed sponsoring of cooperative endeavors may not translate into greater multinational output. This was recently demonstrated by near stagnant levels of integration in transnational enterprises among European Union countries despite explicit and celebrated initiatives to overcome national borders in research efforts, questioning the effectiveness of past and existing measures to overcome national borders [10]. However, our results additionally imply that the development of international collaborations may conform to generic physical principles which may not be sensitive to funding or policy strategies. Therefore, if the number of global ties is bounded, it would be prudent for policy efforts not to gauge collaboration success by numbers, but by how and with whom partnerships are forged in order to maximize efficiency in research practices and returns in scientific or artistic productivity and excellence.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.physa.2015.09.085.

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