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Structure, status, and span: gender differences in co-authorship networks across 16 region-subject pairs (2009–2013)

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Abstract

Global and team science approaches are on the rise, as is attention to the network underpinnings of gender disparities in scientific collaboration. Many network studies of men's and women's collaboration rely on bounded case studies of single disciplines and/or single countries and limited measures related to the collaborative process. We deploy network analysis on the scholarly database Scopus to gain insight into gender inequity across regions and subject areas and to better understand contextual underpinnings of stagnancy. Using a dataset of over 1.2 million authors and 144 million collaborative relationships, we capture international and unbounded co-authorship networks that include intra- and interdisciplinary co-authorship ties across time (2009–2013). We describe how gender informs structural features and status differences in network relationships, focusing on men and women authors in 16 region-subject pairs. We pay particular attention to how connected authors are (first- and second-order degree centrality), attributes of authors' collaborative relationships (including the "quality" and other characteristics of these ties), tendencies towards gender homophily (proportion of same-gender ties), and the nature of men's and women's interdisciplinary and international reach. Men have more advantageous first-order connections, yet second-order collaborative profiles look more similar. Men and women exhibit homophilous attachment to authors of the same gender, consistent over time. There is notable variation in the level of gender disparity within subjects across countries. We discuss this variation in the context of global trends in men's and women's scientific participation and cultural- and country-level influences on the organization and production of science.

Keywords Collaboration networks · Research collaboration · Scientific collaboration · Global science · Team science · Gender · Bibliometrics · Scientific publishing

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Introduction

Over the last several decades, science institutions have seen increased representation of women (Fox et al., 2017b). However, despite this increase, there remains a disproportionate underrepresentation of women in the upper echelons of science, with few women full professors (Finkelstein et al., 2016) or leaders of scientific organizations (EC, 2019). In addition, several studies have shown that gender inequalities in hiring (Moss-Racusin et al., 2012), earnings (EC, 2019; Shen, 2013), grant funding (Ley & Hamilton, 2008), promotion (EC, 2019), publication (King et al., 2017; Xie & Shauman, 1998), and patenting productivity (Ding et al., 2006; EC, 2019; Whittington, 2018) remain. Important influences on these inequalities include a masculine culture and practice of science, structures of inequality that lie in the organization and the arrangement of scientific work, gender bias and gender stereotyping, and the influence of intersecting social institutions such as work, marriage and family (Correll et al., 2007; Fox, 2005; Fox & Nikivincze, 2021; Hunter & Leahey, 2010; Kyvik & Teigen, 1996; National Academy of Sciences, 2007; Schiebinger, 2001; Whittington, 2011). In addition, previous studies have found that building scholarly networks and reputations may be slower processes for women than for men (Cole, 1987; Fox & Freeman, 1989). However, other studies find contradictory results of gender parity or advantages for women in scientific career processes such as grant funding, journal reviewing, and hiring (Ceci & Williams, 2011; Marsh et al., 2009).

As a relational category, gender influences social interactions and operates as a basis of exclusion or subordination within scientific institutions (Long & Fox, 1995; National Research Council, 2001) and research collaborations (Boschini & Sjogren, 2007; Fox, 2001, 2020; Kyvik & Teigen, 1996; Larivière et al., 2013; West et al., 2013). This leaves us with a puzzle: in what contexts and under what conditions does gender shape social networks within scholarly collaborations?

This work builds upon that of previous scholars who apply a network analytical perspective to understand women's position and productivity in co-authorship networks. Results from previous research on co-authorship networks may be ambiguous in part because findings are largely based on case studies. We take advantage of Scopus bibliometric data to employ a cross-regional, cross-subject approach to men's and women's co-authorship trends in an especially broad and comprehensive manner.[1] Our comparative approach

[1] Preliminary results from this analysis are presented in Chapter 4 of the "The Researcher Journey Through a Gender Lens", a report developed through Elsevier (2020a). The current work develops and extends the chapter results: it situates the analysis in existing social scientific theoretical frameworks, includes an expanded set of measures and results, and presents statistical analyses of the findings. The yearset from which the focal authors are drawn (2013) and the co-authorship network is created (2009-2013) remain the same.

focuses specifically on researchers in four academic knowledge subjects (Biochemistry, Business and Economics, Engineering, and Medicine) and four geographic locations (United States, Brazil, Europe (EU28), and Japan). As we discuss later, the selection of different regions and subjects as comparison cases is valuable because they each have different gender norms and standards for women's rights, and vary in women's representation in academic fields. Macro-level features of educational systems, economics, and labor markets influence cross-national variability in occupational gender segregation, particularly in STEM careers (Charles, 2011; Charles & Bradley, 2009). Regional- and subject-specific context may complicate our (existing) generalized understandings of women's and men's positioning in science networks. Large-scale analysis of the relationship between country- and field-level influences on gender equity in science is needed to investigate how uniform, consistent, and/or durable gender disparities are across and within countries, disciplines, and cohorts (Holman et al., 2018). We find that while gender inequality within academia remains a global issue, variation in regional and subject area gender inequality is prevalent and important to consider. Such questions can be addressed with our global and broad network capture and analysis.

Our approach utilizes "complete" co-authorship information for the focal authors in our 16 region-subject pairs—calculating network position based on focal authors' co-authorship relations ties that span a global landscape. Network approaches to collaboration rely on sufficient levels of data "completeness" (i.e. non-missing data) and must not be arbitrarily truncated or bounded. Network approaches can also become hampered with data complexity, as the number of authors and their co-authors increases exponentially as the population grows. For this reason, much past research on gender disparities in science utilizes case study approaches (often single discipline and/or sole country) to draw generalized conclusions about the relationship between gender, network structure, and career inequalities in science. Mono-discipline, localized approaches are often unable to take into account interdisciplinary ties and those that cross bounded sets (Larivière et al., 2013), or to look beyond an author's set of co-authors to see the relationship of first- and second-order ties on authors' productivity and positioning. With access to unbounded global collaborative information, we are able to build on existing research and get better traction on the network underpinnings of men's and women's co-authorship for authors in our 16 region-subject pairs.

Our argument and analysis provides two key contributions to existing scholarship. First, we argue that gender may be entangled in men's and women's differential *structural positions* in collaboration, and also in their *status differences* and *spanning characteristics* of ties. Our data allow for an examination of all three in this analysis. Both co-author attributes and structural characteristics shape opportunities for future collaboration (Madlock-Brown & Eichmann, 2016). For example, an author may collaborate with few very experienced and/or well-connected co-authors. Alternatively, an author may have a relatively large number of collaborators, who themselves have inexperienced or not well-connected co-authors. An author's co-authors may themselves have well-connected co-authors, or they may be relatively isolated from the larger network of collaboration. To this end, we examine how connected authors are (degree centrality), attributes of authors' immediate ties, the "quality" and other resource-rich characteristics of these ties, tendencies towards gender homophily (proportion of same-gender ties), and the nature of men's and women's interdisciplinary and international reach (proportion of collaborators outside of one's core discipline and those affiliated with different countries). We also investigate men's and women's ties to direct and indirect collaborative resources to analyze how network position, prominence, and productivity of co-authors and of co-authors' co-authors vary across regions and disciplines.

Second, our analysis provides insight into the generalizability of trends regarding men's and women's positioning in the social structure of science across regions and subjects. Analyzing collaboration comparatively is valuable because coauthorship has generally only been analyzed within a single country or dataset without separating out the effects of regional and disciplinary differences on academics' collaborations (Abramo et al., 2013; Larivière et al., 2011; Ozel et al., 2014). Considerable institutional, national, and international attention has been devoted to the equity implications of the gender gap in scientific careers, leadership positions, and research. The gap has been steadily closing in recent decades, across the global scientific landscape, with some disciplines and countries moving towards equity more slowly than others (Elsevier, 2017, 2020a; Holman et al., 2018). It is important to examine differences across regions and subjects to gain insight from areas where growth toward equity is accelerating, and to better address contextual, country-, and disciplinary-underpinnings of stagnancy.

Our rich data source allows for an exceptionally detailed study of international and unbounded scientific co-authorship networks that span national boundaries and include intra- and interdisciplinary co-authorship ties across time. This analysis presents descriptive statistics of differences between men and women across region-subject pairs as a first step towards future work in this area. With some important variation across countries, we find that men tend to have more first-order connections, yet the second-order collaborative profiles of men and women look more similar. Gender homophily in co-authorship is notable and consistent over cohorts; men and women exhibit homophilous attachment to authors of the same gender.

Gender, collaboration, and productivity

Gender informs collaboration opportunities for men and women in science (Fox, 2001; Fox & Mohapatra, 2007; Boschini & Sjogren, 2007; West et al., 2013). Research on the influence of status beliefs—cultural stereotypes that relate to the competence and worthiness of particular groups surrounding an activity—highlights the primary role that gender plays in the maintenance of inequality in work settings (Ridgeway, 2011). Past research finds that women are more limited in their access to formal and informal collaboration networks and opportunities (Rhoten & Pfirman, 2007). Women's networks generally are also higher-density and have more localized information (Smith-Lovin & McPherson, 1993).

A growing body of work reveals that gendered dynamics of collaboration in science influence women's differential publishing and patenting activities compared to men (Ding et al., 2006; Larivière et al., 2013; Meng, 2016; West et al., 2013; Whittington, 2018; Xie & Shauman, 1998, 2003; Zeng et al., 2016). Several studies find men and women are equally likely to publish collaboratively (Cole & Zuckerman, 1984; Hunter & Leahey, 2008; Rhoten & Pfirman, 2007), especially among top scientists (Abramo et al., 2019b). Accounting for tenure, discipline, active grants, and professional age, however, some studies find that women have more collaborators than men (Bozeman & Gaughan, 2011). This is consistent with research on patent collaborations, which finds that women have more co-inventors per patent than men but that women have fewer total patent collaborators than men over their careers, a result of women being assigned fewer patents (Whittington, 2018). This smaller number of collaborators also holds in the realm of publication productivity, where women scientists have fewer distinct co-authors than men over their careers, a difference explained by lower publication rates and shorter career lengths (Zeng et al., 2016). Fox and Nikivincze (2021) find that controlling for rank (a proxy for career length) and for those that have a wider "span" of collaboration eliminates gender gaps in productivity at the high tails. Other research finds that collaborator characteristics are important. Women are less likely to repeat collaborations with previous co-authors than men (Zeng et al., 2016), and to collaborate internationally (with some regional and subject variation) (Frehill et al., 2010; Larivière, et. al., 2011; Fox et al., 2017a, 2017b). Finally, women are more likely to choose research collaborations based on a mentoring strategy (Bozeman & Corley, 2004; Bozeman & Gaughan, 2011), and thus mentoring relationships may be especially important for women's collaborative productivity (Kiopa et al., 2009; Sands et al., 1991). Even after forming collaborations, however, women's resulting papers tend to be less visible than men's (Larivière et al., 2013). The effects of perceived differences in research quality and evaluation may make female scientists less likely to be invited to collaborate (Knobloch-Westwick et al., 2013). Gender clearly informs women's and men's collaborative profiles and career activities, and the challenges of network analytic work often lead researchers to focus on particular cases to deeply assess these dynamics.

While some cases find evidence of parity in commonly referenced network analytic measures, others find women's network positioning to be qualitatively different from men's, or cumulatively disadvantaging or advantaging. Our analysis contributes to our understanding of the generalizability of gender differences in co-authorship network positioning across region and field with respect to these common measures in the network literature. We combine two classic understandings of network positioning to address men's and women's network positioning in co-authorship networks—taking into account not only *how* scientists are positioned in the co-authorship landscape, but also *who* they are connected to and who their co-authors' co-authors are. Actors may have what are considered to be "structural" opportunities by virtue of ready access to co-authors and co-authors' co-authors, or they can be relatively isolated and peripheral. Regardless of position, an actor's tie relations can be infused with status and be resource-rich and reaching across subjects, or they may be insular, inward, and short on value. We focus on three aspects—*structural features* of positioning*, status differences* in current and recent co-authorship relationships, and differentiation between men and women across regions and subjects in international and interdisciplinary *span*—and we use our expansive dataset to focus on these in our cross-region, cross-subject analysis.

Structural features of men's and women's positioning

Structural opportunities can stem from multiple aspects of a scientist's location in the career trajectory that lead to increased opportunity (Moss, 1977). For example, a scientist may be structurally advantaged by virtue of a position of power or authority in a research group, or through a position in key roles in a lab. In this analysis, we focus on structural opportunities that may stem from one's position at the confluence of other key collaborative relations. In particular, structural positioning in the dense web of co-authorship relations, specifically their centrality or peripherality in access to others in the network. Centrality to others in collaborative relations has been shown to publish more articles, in higher impact journals, and accrue more citations (in a faster amount of time) (Lee & Bozeman, 2005), and have been shown to be related to mechanisms of status inequality more broadly (Ibarra, 1992, 1997).

To understand how gender may play a role in characterizing diverse conditions of research collaboration, we focus on the average first- and second-order degree centrality (connectivity as measured by the number of unique first-order collaborators) that men and women authors hold. *First-order degree centrality* measures the number of direct collaborators, or the number of unique authors with whom the focal author co-authored during a specific time period. For instance, the co-authors on this paper share first-order degree centrality as a result of this collaboration.

Having a higher first-order degree centrality places a scientist in a more advantageous network position. We also consider the connectedness of a focal scientist's second-order collaborators. *Second-order degree centrality* takes into account the co-authors of one's co-authors. Second-order degree centrality may be considered a measure of the focal authors' network "reach" to available social capital contained in their immediate network. If a focal author's average number of second-order collaborators is high, this indicates that the focal author has potential access to direct collaborators with many additional connections to share and help create future bridging ties. While a focal author may be connected to only a few immediate ties, these may be "well-connected" to any others, compared to a being tied to many others that themselves are less connected in the social structure of academic science.[2]

Status differences in men's and women's collaboration

In addition to helping to shape advantageous positions in a collaborative network, status processes also influence the characteristics of one's co-authors (and co-authors' co-authors). Scholars seek to collaborate with high-status scientists, since one's own status is influenced by—and influences—the status of those with whom one associates (Bonacich, 1987; Gould, 2002; Leifer, 1988). For example, gendered processes inform authorship order and the key roles that women assume in the research process (Macaluso et al., 2016; West et al., 2013). There are fewer women in senior positions in most disciplines and fields, a fact which also guides co-authorship interactions (Gaughan & Bozeman, 2016). At the same time, status beliefs about gender shape men's and women's expectations of themselves and others, which in turn shape interactions (Moss-Racusin et al., 2012; Ridgeway, 2011).

A prominent example of status-based processes in science is the tendency toward homophilic collaborative relations. Scientists tend to collaborate with others of their same gender (Ferber, 1988; McDowell & Smith, 1992; NSF, 2004; Bozeman & Corley, 2004; Ferber & Brün, 2011; Whittington, 2018; Holman & Morandin, 2019; Wang et al., 2019). These trends exist despite mixed-gender collaborations being more productive and more central in collaboration networks (Ghiasi et al., 2015). The tendency to form homophilous ties implies that the unequal gender composition in most academic disciplines will put women at a disadvantage in forming coauthorship networks. Homophily and status beliefs about gender thus exacerbate gender bias, as the cumulative advantage of status-biased

[2] We focus on these two foundational measures for our initial analysis but could consider other relevant measures in future work, including brokerage, measures of aggregate constraint (Burt, 1998, 2004), clustering coefficients, density of overlapping ties between first and second-order ties, and reachability to otherwise unattached others. Given the size of this network and its computational complexity, the evaluation of these across 16 region-subject pairs, and inclusion of status characteristics (presented next), we leave these additional fruitful measures to future research.

interactions shape collaboration opportunities and scholarly recognition (Knobloch-Westerwick et al., 2013; Rossiter, 1993). In this analysis, *first-order collaborators' gender composition* measures the share of direct collaborators by gender.

Status attributes inform additional aspects of the collaborative process. Collaborative networks tend to follow laws of preferential attachment, in which highly connected (or otherwise high-status) others increase their connectivity faster than less-connected counterparts (Barabási et al., 2002; Jeong et al., 2003; Wagner & Leydesdorff, 2005). We examine the tendency for men and women authors to hold first-order ties of similar prominence. In particular, we focus on the *average level of productivity of focal men and women authors' first-order collaborator*s and the tendency to connect to those with longer *publication tenure.* Widespread average differences among first-order collaborators in men's and women's collaborative portfolios may stem from biases in status processes that lead to preferences for higher-status individuals in working relationships more generally (Holman & Morandin, 2019).

Spanning ties across disciplines and regions

We also contribute to a deep literature seeking understanding of the ways in which men and women foster interdisciplinary ties (Rhoten & Pfirman, 2007; Sugimoto & Weingart, 2015) and/or engage with researchers internationally (Uhly et al., 2017; Zippel, 2017). Rhoten and Pfirman (2007) suggest a lean in the literature towards findings of women's increased engagement of interdisciplinary (as opposed to single-discipline) approaches compared to men. This work varies with respect to the operationalization of principal mechanisms of interdisciplinarity—including idea cross-fertilization, team-collaboration, field-creation, and problem-orientation—yet finds significant variation between men and women across this variety in areas of engagement. Indeed, intrapersonal, interpersonal and socio-structural factors may contribute to decisions about interdisciplinary research, and certainly structural and status factors that inform gender are likely to relate to differences in engagement between men and women. Others—looking across countries and specifically toward publishing trends—have found more parity in the proportion of women and men that evidence high interdisciplinarity in their scholarly output, however (Elsevier, 2017). Our dataset allows for us to examine the full set of collaborative relations authors hold, including those across subjects. There are many ways to measure a researcher's level of interdiscipline engagement; knowledge production can be analyzed using the categories of "people", "publications", as well as "ideas" (Sugimoto & Weingart, 2015). While no single indicator will capture or adequately address the whole of a researcher's activity across disciplines (Wang & Schneider, 2020; Digital Science et al., 2016), we focus here on characteristics of men's and women's co-authors. *Interdisciplinary reach* measures the share of a focal author's direct collaborators who publish outside of the focal author's subject areas. This enables us to operationalize how collaborators integrate "information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge" (National Academy of Sciences, 2005, p. 188).

In addition, more and more scholars collaborate across institutions, disciplines, and country boundaries (Elsevier, 2017; Gazni et al., 2012; Larivière et al., 2015; Leahey, 2016); those who do tend to produce publications with higher average impact (Adams, 2013; Abramo et al., 2019a; Chinchilla-Rodriguez et al., 2018) and exhibit higher productivity (Barjak & Robinson, 2008). Collaborations by women are more likely to be domestic than are collaborations by men (Abramo et al., 2013; Larivière et al., 2013; Zippel, 2017). These trends may be partly a result of women's greater concentration in fields where international collaboration is less common (Aksnes et al., 2019), although research suggests that social dynamics of preferential attachment may also be in play (Wagner & Leydesdorff, 2005). Gender also informs differential rewards for global collaboration. While women are less likely to participate in global science (Uhly et al., 2017), findings differ by discipline and cohort (Kwiek & Roszka, 2021). Further, the globalization of academic science can bring unique opportunities for marginalized groups and help circumvent closed home science communities (Zippel, 2017). Our measure of *international reach* captures the share of direct collaborators who are affiliated with a geographic region different from that of the focal author.

Variation across region and subject

A key focus of this analysis is the consistency and/or variation in gender disparity across and between regions and subjects. The selection of different regions as comparison cases is valuable because they hold different gender norms, different expectations of gender equality, and different standards for women's rights (Mason et al., 2013; World Economic Forum, 2020). Further, countries maintain different cultures of science and scientific practice, and these are linked to specific hierarchies in scientific organization, cultural emphasis on science and science values, financial compensation and reward. While some large-scale scientometric research includes country-level disaggregation, findings are often aggregated across countries or presented disaggregated without further interrogation (Huang et al., 2020; Larivière et al., 2013). Larivière et al., (2015) and Chan and Torgler (2020) examine country-level indicators of human development and gender equity, and find that countries ranked in the lowest quartile for these had the lowest levels of women's scientific output. This work dovetails with that of country-specific trends in women's involvement in STEM more broadly. Charles (2011) and Charles and Bradley (2009) explore sex segregation in the field of study, and find that sex-typing of curricular fields is stronger in more economically developed contexts. They suggest that structural features of postindustrial labor markets and modern educational systems support the development of cultural influences on gender-specific curricular affinities for particular fields and movement towards gender equity more generally (Charles & Grusky, 2004). While the focus of this past research is on individuals' selection of a field of study, an implication is that culturally- and country-specific factors may also shape career pathways within the science realm and collaborative context. It remains an open question how cultural and country-specific factors relate to men's and women's network positioning in the global structure of science collaboration.

Furthermore, the representation of women varies across disciplines, and this shapes options for gender homophilous tendencies (Holman & Morandin, 2019). Subjects also vary in support for interdisciplinarity, which influences the availability of gender-homophilous interaction. Regional and cultural differences in women's participation in science, which are changing over time, also affect the propensity for gendered interactions and trends (Charles, 2011; Charles & Grusky, 2004). Finally, across regions and disciplines, the representation of women is generally increasing, and in some countries and subjects dramatically so (Elsevier, 2017). Age stratification and cohort effects in scholarly communication are thus tantamount (Sugimoto et al., 2016); seniority and experience anchor the collaboration process and shape immediate and future opportunities for authors, as we discuss below. We examine the generality of gendered trends across subjects and regions with varying levels of men's and women's participation, and we also assess if there are intergenerational changes afoot across cohorts of academics.

We consider these contextual differences between geographic areas and disciplines in women's representation and participation in region-subject pairs. We focus on four regions to use as comparative cases in this analysis: Brazil, Japan, USA and the EU28. These four were selected for our analyses because they were expected to reflect a variety of research cultures and have different ratios of women to men among authors (Elsevier, 2017).[3] The regions vary in the extent to which men and women diverge in economic opportunity, educational attainment, health outcomes, and political involvement, with Japan and Brazil falling behind the United States and most countries in the EU28 in measures of the global gender gap index (see, for example, World Economic Forum, 2020). Yet, country-specific context remains important (Haghani et al., 2022). For example, while Brazil has one of the highest global gender gap indices in Latin America, the country's disparities are concentrated in areas related to economic and political opportunity, while it demonstrates higher levels of parity between men and women scientists in scientific and technical involvement and productivity (Elsevier, 2017; World Economic Forum, 2020). In our sample, the US, EU28 and Brazil have similar proportions of women researchers, with 28.5%, 35.6%, and 42.6%, respectively. In contrast, Japan's gender gap in political and economic attainment is one of the largest among all advanced economies, and growing (World Economic Forum, 2020), and the percentage of women scientific and technical authors in our sample remains low (12.0%).

Similarly, we choose Biochemistry, Business and Economics, Engineering, and Medicine as a sample of subjects from four broad disciplinary clusters—life sciences, social sciences, physical sciences and health sciences, respectively. We do not intend each subject to be wholly representative of these subject-area clusters; rather, they represent subjects with different ratios of women to men among authors (Abramo et al., 2013; Elsevier, 2017; European Commission, 2019), with sufficient sample size across regions, and who are distinct from other disciplinary clusters. Medicine and Biochemistry are among those research areas with relatively higher ratios of women to men across subjects whereas Engineering and Business & Economics are among those subject areas with relatively lower ratios of women to men (Elsevier, 2017, 2020a).

[3] Additional data limitations with respect to gender disambiguation also dictated our decision-making about country selection. Names that have to be translated into the Roman alphabet often represent a challenge for name prediction algorithms, where gender can be conveyed in tone and presentation of the character. This complicates analyses where gender prediction is central to the analysis, and for these reasons, we do not include countries such as China here. See Elsevier (2020a), page 45 for additional details. The selection of regions and subjects mirrors those selected for related reports, and thus supplement and extend the details provided on these regions and subjects in other reports (Elsevier, 2017, 2020a).

Table 1 Characteristics of the network relationships

Network feature	Total N
Actively-publishing authors (i.e. those who published between 2009 and 2013 and included in network boundary set)	10,470,713
Number of ties among *actively-publishing authors*	144,347,507
Focal authors (actively-publishing authors who published in 2013 in the subjects and regions selected in the study)[a]	1,271,488
Focal authors coded as women	395,996 (31.1%)
Focal authors—regional affiliations	
EU28	661,911
United States	445,046
Japan	128,277
Brazil	54,064
Focal authors—subject area affiliations	
Medicine	728,143
Biochemistry	459,195
Engineering	324,025
Business and Economics	53,801

[a]Focal authors published in 2013 and were active in 2009–2013 with at least two publications during the study period 2009–2013, or authors with their first publication during 2009–2013, in subjects and regions selected for this study. Note that the total number of focal authors listed is fewer than the sum of those in regions or in subject areas because focal authors may be in more than one region and/or subject

Methods

Dataset

Focal authors and co-authorship network

Our bibliometric data are drawn from the Scopus database, which includes 1.7 billion citations to articles, conference papers, and reviews. Scopus uses an author-matching algorithm to assign each author a unique identifier, disambiguating authors with the same last names using all available information from publications (including subject area, author affiliation, and co-authors). This is enhanced by author feedback through Scopus and links with ORCID (Open Researcher and Contributor ID). There are 17 million author profiles in Scopus.[4]

We define *actively-publishing authors* as the set of 10.4 million authors who published at least two publications during the study period 2009–2013 or published their first

[4] Although notably comprehensive, one limitation of the Scopus dataset (and many like it) is coverage of non-English written journals, and this could impact the collaborative networks of those in other countries. We do not anticipate this to impact men versus women differently in those countries, however, and thus this should not influence our conclusions about gender differences within region-subject pairs.

publication during this period (to ensure we include junior scholars) (Table 1).[5] We define *focal authors* as the set of 1.3 million actively publishing authors who meet four criteria:

(1) They are members of the network of *actively-publishing authors*;
(2) They published at least one publication in 2013 in the subject(s) and region(s) selected in the study;
(3) They have a first name associated with their publishing record; and
(4) We could predict gender for their name (more on this in a later section).

For ease of data presentation, we only present analyses from authors in the focal set who first published after 1989 (although all research-active authors in the Scopus dataset are included as collaborators). Authors who first published in 1989 or after represent 87.4% of the focal authors across all years. Our substantive conclusions do not change if we include trends for this group in our results.

Authors were allocated to a region if more than 30% of their publications during the period indicated an affiliation with that region. Authors with multiple institutional affiliations in different regions on their publication(s) are classified as members of multiple regions. We treat countries in the EU28 as a region rather than as single countries, based in part on regional dynamics in the European Union that promote collaboration, activity, and mobility trends that mimic other geographic regions (such as the United States) (Elsevier, 2013).

Authors were ascribed to a subject area if more than 30% of their publications during the period (2009–2013) were published in a journal with that classification. Publications are classified into subjects using the Scopus journal classification, *All Science Journal Classification* (ASJC). In this system, journals in Scopus are categorized under four broad subject clusters (life sciences, physical sciences, health sciences and social sciences), which are further divided into 27 major subject areas and additional granular subcategories within these (for more details, see Elsevier, 2020b, 2020c). From these, we selected four subject areas for analysis: Medicine, Biochemistry, Engineering, and the aggregate Business & Economics.[6] Journals may be classified into one or more of these subcategories based on their content; those that are not discipline-specific such as *Nature* and *Science* fall under the classification "multidisciplinary."[7] As with regional classification, authors with 30% or more of their publications in journals classified in multiple subject areas are represented in each of those subjects in the analysis.

[5] The study period was selected to retain comparability to the Elsevier report (2020a), which closely follows the same set of focal authors across regions. We select authors active in the 2013 year, and include authors of all years of publishing experience. It is possible that gender disparities lessened in our region-subject pairs since 2013, although progress towards equity tends to come in fits and starts, does not include all scientists across contexts, and does not always move forward (Charles & Bradley, 2009; Charles, 2011). The COVID-19 pandemic and the resulting gender disparities in productivity during pandemic work conditions also shed light on these dynamics (King and Frederickson 2021).

[6] The subject area of business & economics was created by aggregating two major subject areas: "Business, Management and Accounting" and "Economics, Econometrics and Finance." We combined these categories because we observed high (i.e., greater than 40% in some cases) representation of authors in both subject areas (Elsevier 2020a). Furthermore, previous analyses revealed that both subject areas had similar ratios of women to men (Elsevier 2017).

[7] Publications in "multidisciplinary" journals were re-classified for the original report into the appropriate subcategories based on the text in their titles and abstracts (see Elsevier 2020a for additional details).

The final set of focal authors is 1,271,488 (Table 1). Of them, 875,492 are men and 395,996 (31.1%) are women. While we focus on focal authors in these particular regions and subjects, we include data on their connections that reach beyond these boundaries to capture the whole of an individual's collaborative efforts during this time, wherever and with whomever they may be located. We utilize the full network of all actively-publishing authors (all years 2009–2013, and all fields and subjects) to generate the network of co-authorships for the final sample of focal authors who published in the year 2013. Our network of collaborators is drawn from the set of actively-publishing authors in Scopus who published between 2009 and 2013 and are connected within two ties to our focal authors. Thus, while all actively-publishing authors are included in the network as co-authors (and therefore inform the network positioning of focal authors), we report specifically on our focal authors in our analysis. Online Resource 1 includes raw counts across all dimensions, including the number of observations by gender within each subject area, region, and cohort. We use the 5-year network window to capture on-going and repeated co-authorship ties, with the understanding that this designation captures network and productivity statistics that are bounded in time and not necessarily characteristic of an author's "full set" of co-authors and collaborative activities across a career.

Key sample characteristics

We group authors into cohorts based on when they first published, defined as length of time since first publication until 2013. We use first publication date as a proxy for age, to assess how generational effects contribute to gender parity. Although scientists from all cohorts are present in the network, we present statistics by cohort in 5 year windows to compare authors with similar years of publication experience as follows: 1989–1993, 1994–1998, 1999–2003, 2004–2008, and 2009–2013.

A multi-step name-matching algorithm (NamSor API, January 2019 release) was used to predict the gender of active authors based on first names, country of origin (defined as the country in which the author published the most papers in their first publication year), first name, and last name.[8] Only those focal authors with a determinable first name were included in the analysis.[9] For more detail on this method, please see the methodological appendix of Elsevier (2020a, pp. 122–123). Using the NamSor API, we inferred gender for 70.1% of authors who published between 2009 and 2013, or 7,749,293 authors.

[8] NamSor treats gender as a binary variable and is only able to infer the gender as "woman" or "man." We acknowledge that this poses a limitation to fully assessing gender inclusiveness. The use of algorithms to predict the gender of individual authors also has important methodological and ethical limitations (Lockhart et al., 2023). We are not asserting that our algorithm correctly identifies the gender identity of all individuals in the resulting dataset, but rather that the aggregate statistics provide insight into gender's effects across the population.

[9] If there was only a single first name associated with an author profile, and if the name was of zero length, these names were excluded from the prediction analysis. When the name was not of zero length, nonsensical characters ["-!#&"] were removed from the beginning or end of the name. When multiple first names were associated with an author profile, the process selected the longest. For example, if an author profile had the first names "Samantha", "#Sam", "Sam", and "S. E." associated with it, the process would identify "Samantha" as the best first name.

Table 2 Measures calculated for focal authors

Measure	Definition	Formula, if applicable
Number of publications	The number of publications by each focal author during the period 2009–2013	
Publication tenure	The number of years from year of first publication until 2013 (or last year of publication) for focal authors	
First-order degree centrality	The number of first-order collaborators, i.e. number of unique authors with whom an author has co-authored papers during the 5 year time period (2009–2013) Note: After conducting sensitivity analyses, we do not exclude any authors with degree centrality measures that are outliers (such as hyper-authored papers)	$d_i = \sum_j a_{ij}$ where $A = [a_{ij}]$ is the adjacency matrix describing the connections among all the authors in the network, such that the entry a_{ij} is equal to one if there is a link (collaboration) from i to j, and zero otherwise. The count of first-order collaborators of an author i, or, equivalently its degree d_i in the network of collaboration
Second-order degree centrality (First-order collaborators' degree centrality)	The average degree centrality of an author's first-order collaborators, i.e. the mean number of first-order ties of first-order collaborators	The mean degree of an author i's first-order collaborators j is defined as follows: $< d_j^i >= mean(d_j^i)$ where d_j^i represents the degree of i's first-order collaborators and d_i the number of first-order collaborations
First-order collaborators' gender composition (homophily)	Proportion of first-order collaborators who are the same-gender as the focal author	
Interdisciplinary reach	Share of first-order collaborators who did not publish in same subject area(s) as the focal author	$interdisciplinary\ reach_i = 1 - (d_S/d)$, where S is the subject(s) where the focal author has published at least 30% of their publications during the prior 4-year period; d is degree (the number of collaborators of the focal author); and d_S is the number of collaborators who have also published at least 30% of their publications in subject S

Table 2 (continued)

Measure	Definition	Formula, if applicable
International reach	Share of first-order collaborators who are not affiliated in the same region(s) as the focal author Note: The EU28 region is here treated as a unique geographic area, meaning that an international collaborator for an author who is affiliated with at least one European country is any author affiliated with a country outside the EU28 region[a]	$international\ reach_i = 1 - (d_R/d)$, where R is the region(s) where the focal author has published at least 30% of their publications during the prior 4-year period; d is degree (the number of collaborators of the focal author); and d_R is the number of collaborators who have also published at least 30% of their publications while also affiliated with region R
First-order collaborators' mean publication count	Authors' first-order collaborators' average number of publications in the period 2009–2013	
First-order collaborators' mean publication tenure	Authors' first-order collaborators' average number of years from year of first publication until 2013 (or last year of publication)	

[a]We find similar results when using an alternate classification for EU28 authors that defines international reach as collaboration across any country line

Measures

Table 2 presents details of all measures collected and formulated on our focal authors. A few deserve further explanation here. We calculate second-order degree centrality as the average number of collaborators of a focal author's direct collaborators. Our measure of interdisciplinary reach is assigned based on the subject areas to which a focal author's publications are classified. Publishing an article together in the same journal (and therefore with the same subject classification) does not necessarily imply that two collaborators are classified in the same subject. It may be the case that one collaborator (or both) may not be assigned to the same subject, as they tend not to publish regularly in that topic.[10] International reach is similarly based on the number of ties with at least 30% of their papers affiliated with a region different from that of the focal author. International reach for EU28 authors was calculated based on collaborations with authors assigned to countries outside the EU28; however, similar results are reported when defining "international collaborators" as those outside of the EU28 focal author's country (Elsevier, 2020a, results not shown). We use all available observations for each measure; therefore, the amount of missing data varies slightly across measures.

We present statistical tests of distributions between men and women using bivariate nonparametric statistical tests for all measures, and include these for all cohort, discipline, and regional subgroups.[11] We use a Wilcoxon Rank Sum test of difference to evaluate the difference because the data are not normally distributed and the gender groups are independent samples. We caution against over-interpreting statistical tests that fail to reject the null hypothesis of no difference between men and women when the sample size is low.

Results

We analyze a set of 1,271,488 focal authors, or members of a network of actively-publishing authors who published in 2013 and for whom we can predict gender for their first name. The representation of women grows over time in each of the 16 "region-subject" pairs, but varies in intensity across them. The highest proportion of women are in Biochemistry, and the lowest in Engineering (Table 3). Regions that have a larger proportion of women among researchers also tend to have a larger proportion of women among researchers within each subject area. Thus, while the trends across regions in the broad subject areas are similar, Japan has the least share of women among researchers across subjects compared to the US, EU28 and Brazil.

[10] Research that examines multi- or interdisciplinarity has engaged a number of indicators or metrics that measure the concept, and research findings and implications can be greatly dependent on the choice of measure (Wang & Schneider, 2020). In addition to the choice of measure, there are additional considerations that need to be taken into account regarding the classification systems used by large data sources to capture interdisciplinarity (Digital Science et al., 2016). Our focus here is on the relative differences between men and women focal authors within regions and subjects, and we utilize a measure that focuses on multidisciplinary engagement that comes from cross-discipline co-authorship connections (as opposed to within publications or grants, etc.). This is but one possible view of focal authors' interdisciplinary engagement.

[11] In some cases, small sample sizes present challenges for the statistical analyses, and we do not present summary statistics for cohort-region-discipline groups when $n < 10$.

Table 3 Ratio of women to men by region and subject area (across all years of first publication 1989–2013) and share of women authors by region and subject area (for selected cohorts)

Region	Subject area	Ratio of women/men	Share of women authors by cohort (Year of first publication)		
		All years (1989–2013)	1999–2003 (%)	2004–2008 (%)	2009–2013 (%)
EU28	Medicine	0.73	35.9	41.4	51.3
	Biochemistry	0.81	39.5	44.3	52.5
	Engineering	0.22	15.3	17.5	20.9
	Business & Economics	0.42	22.0	27.5	34.9
USA	Medicine	0.54	31.3	34.7	41.6
	Biochemistry	0.44	26.9	28.9	35.6
	Engineering	0.14	10.6	11.8	14.5
	Business & Economics	0.30	21.5	24.4	28.3
Japan	Medicine	0.18	9.4	12.6	20.8
	Biochemistry	0.19	10.3	13.6	21.7
	Engineering	0.05	3.7	4.4	6.7
	Business & Economics	0.14	9.1	8.5	15.0
Brazil	Medicine	0.97	46.0	47.5	52.1
	Biochemistry	1.02	47.1	48.6	52.8
	Engineering	0.27	14.3	19.4	23.6
	Business & Economics	0.37	22.4	15.8	29.0

We present our results as a series of figures that group region-subject pairs by cohort. Co-authorship and citation data are notoriously skewed, and our data are no different. The supplementary information shows mean and median number of publications as well as average publication history lengths (Online Resource 2). The data suggest that men have, on average, greater productivity than women across region-subject area pairs. The only exception is we find no difference in median productivity by gender in B&E in Japan. More generally, men also appear to have longer publication histories than women across all regions and subjects.

Gender differences in network structures of opportunity

We begin with a measure of position based on the number of distinct co-authors men and women maintain in their authorship network in a 5-year period—in network terms, *first-order degree centrality*—and examine gender differences in degree centrality across our 16 region-subject pairs. We consider these gender differences across scientist cohorts, defined by year of first publication, in each region-subject group (Fig. 1). Across regions and subjects, we see a consistent trend in first-order degree centrality: the largest gap between men and women exists among the most senior cohort of authors, and this gap shrinks among more recent cohorts. Of course, we cannot assess whether the larger gender gap in first-order degree centrality among older cohorts is a cohort effect (i.e. change in the nature of

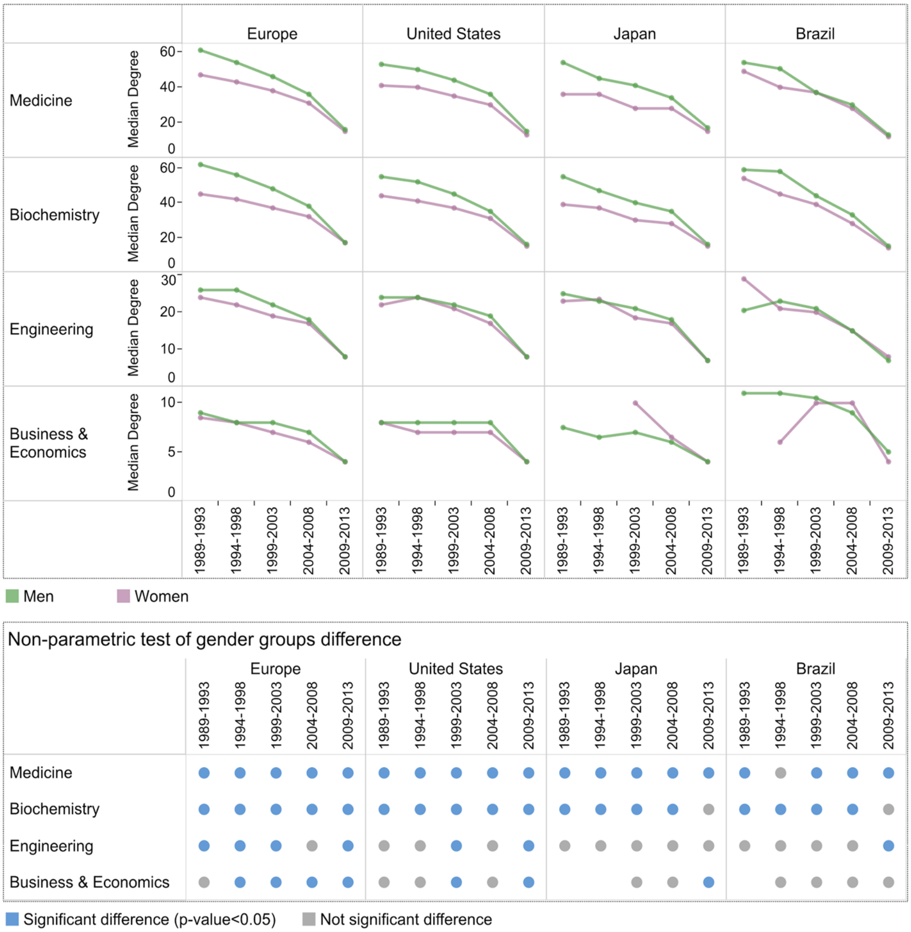

Fig. 1 *Above panel*: Median (by subgroup) of focal authors' first-order degree centrality. Subjects and regions are ordered from top to bottom and left to right, respectively, according to descending author count. Average values corresponding to fewer than 10 observations have been excluded from the analysis. Y-axis scales vary by subject. X-axis displays cohorts by region. *Below panel:* Significance of Wilcoxon Rank Sum test of difference between the two gender groups in each subject-region-cohort. Source: Scopus

disparity over time), the result of cumulative disadvantage, or (likely) both. Medicine and Biochemistry exhibit more stark differences between men and women than other subjects. In Engineering and B&E in Japan and Brazil, we note more variable trends across cohorts. This may be due to a small number of observations for each cohort (i.e. non- parametric test of the difference between men and women in the below panel of Fig. 1).[12]

[12] For completeness, we included focal authors of Japan and Brazil in Engineering and B&E and more senior cohorts of EU28 focal authors in B&E, which have small numbers of observations. The aggregate statistics for these groups are not reliable and can generate fluctuating trends. We intentionally avoid interpreting these results.

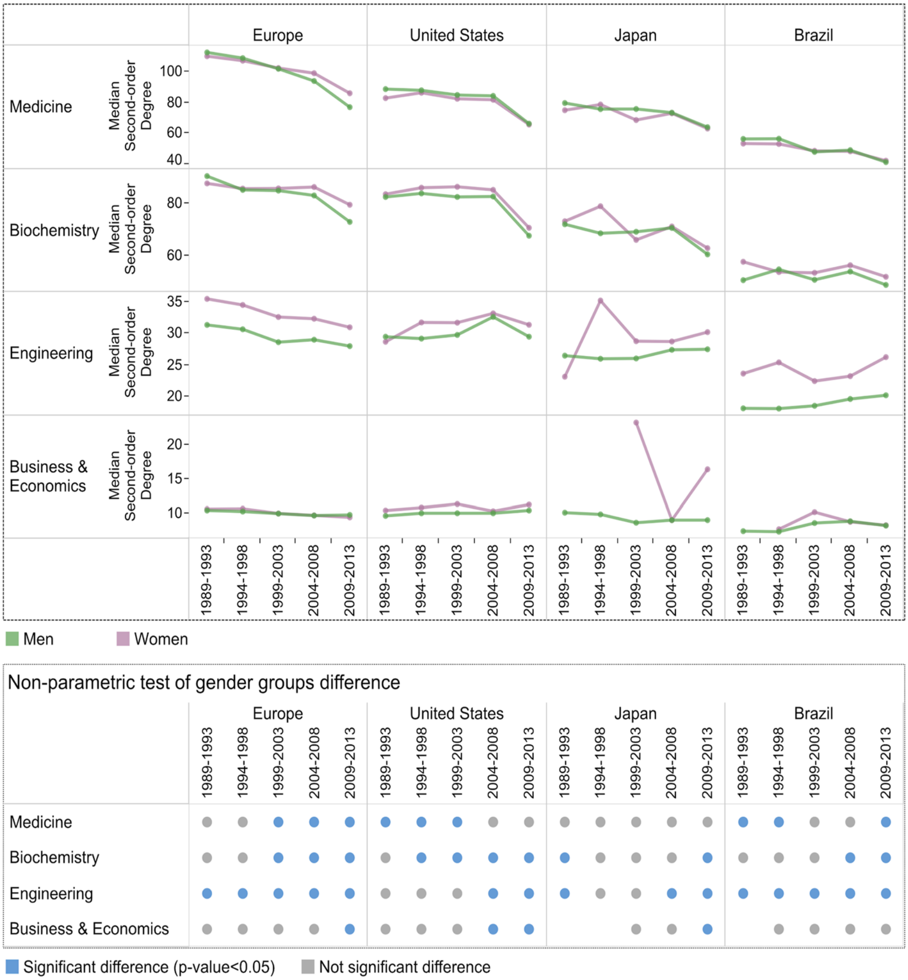

Fig. 2 *Above panel:* Median (by subgroup) of focal authors' second-order degree centrality. Subjects and regions are ordered from top to bottom and left to right, respectively, according to descending author count. Average values corresponding to fewer than 10 observations have been excluded from the analysis. Y-axis scales vary by subject. X-axis displays cohorts by region. *Below panel:* Significance of Wilcoxon Rank Sum test of difference between the two gender groups in each subject-region-cohort. Source: Scopus

In contrast to first-order ties, men and women are more similar in their patterns of connection to others through their second-order collaborators (Fig. 2). Across cohorts, men and women foster ties with similar median second-order connectivity, and in many instances (such as Engineering) women exhibit higher levels of second-order tie connectivity. In Medicine in the USA, women have lower second-order degree centrality, and the gap gets wider for more senior cohorts. However, in the EU28, the pattern is the opposite; women have higher second-order connectivity levels compared to men, and the difference disappears in senior cohorts. Second-order degree centrality fluctuates in Engineering and B&E across all regions, which may be due to small numbers for these cohorts. In addition, while the gender gap in first-order degree centrality shrinks in more senior cohorts, there is a less dramatic difference between the second-order degree centrality of men and women in more senior cohorts compared to more junior cohorts (Fig. 2). There thus appears to be some stabilizing effect of second-order degree on structure as it pertains to gender differences between men and women.

These findings have implications for our understanding of men's and women's scientific productivity. Men and women do not differ significantly in the nature of their co-authors' collaborative tendencies, consistent across region-subject pairs. While women evidence fewer publications and collaborators than their men colleagues, their co-authors hold similar levels of connections. This may imply that this is not necessarily a story of "double-disadvantage," where women collaborate less and with less collaborative co-authors.[13]

Gender differences in characteristics and status of collaborators

Research has demonstrated that the "quality" and characteristics of men's and women's networks of social relations often turns on status-based inequities, depending on the nature of the activity and context of action. We consider the characteristics of men and women author's collaborators and assess gender disparities in the level of seniority and publication experience present in co-authorship connections. We also consider whether and how men's and women's co-authorship relations are defined by gender-, disciplinary-, and regional-level homophily.

Co-author homophily

Our results demonstrate resoundingly the universal dynamic of gender homophily in collaborative profiles across region-subject pairs. Women authors tend to collaborate more with women than men (Fig. 3), and men tend to collaborate more with men than women (Online Resource 3 in the Supplementary Information), across subjects, regions, and cohorts, with the exception of B&E in Japan.[14] These findings corroborate those found in other collaboration network studies (Holman & Morandin, 2019; McPherson et al., 2001; Whittington, 2018). The data also reveal that men's and women's levels of homophily tend to be greatest among those with the least publishing experience (i.e., more junior cohorts).

High-status collaborators: first-order productivity and tenure

One's collaborators can bestow a marker of status and, in so doing, have the potential to influence one's own research productivity. Our data show that men and women have

[13] Future research may want to consider the potential of gender differences in the redundancy of first- and second-order collaborators. That is, second-order ties may be shared by first-order connections, or triads may be closed among the first-order connections, such that there is no tremendous benefit from having these second-order connections. If women (or men) have more closed networks—despite similar median second-order degree centrality scores—this could be differentially beneficial or harmful to their careers (Granovetter, 1973; Hansen, 1999).

[14] The share of women and men collaborators for focal authors within a country and discipline does not quite add up to 100% because of the missing gender information on some authors. If all authors could be assigned a gender, then for either women or men focal authors, the sum of the share of women collaborators (Fig. 3) and the share of men collaborators (Online Resource 3) would add up to 100%.

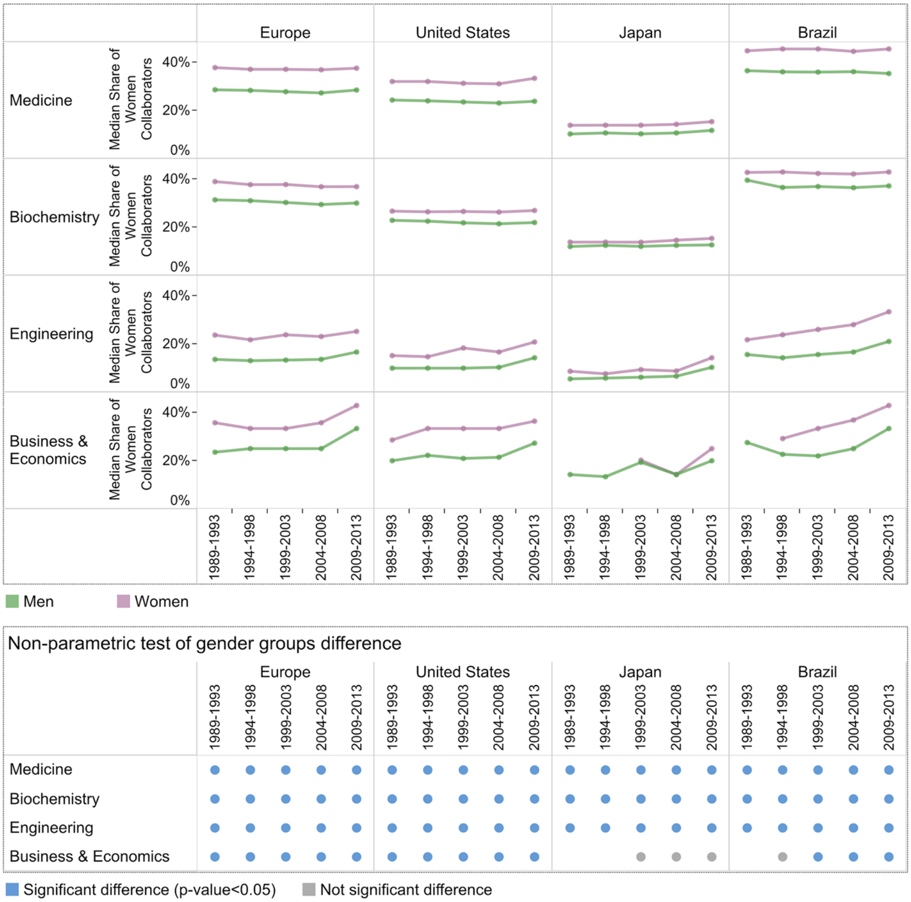

Fig. 3 *Above panel:* Share of women collaborators (median by subgroup). Subjects and regions are ordered from top to bottom and left to right, respectively, according to descending author count. Average values corresponding to fewer than 10 observations have been excluded from the analysis. X-axis displays cohorts by region. *Below panel*: Significance of Wilcoxon Rank Sum test of difference between the two gender groups in each subject-region-cohort. Source: Scopus

co-authors with similar productivity levels (measured as median publication count in the period 2009 to 2013, Fig. 4) and publication tenure (Fig. 5) across subjects and regions. A notable exception is the field of medicine in EU28 and the USA, where men partner with collaborators that are more productive than women, on average. There is also a trend among more junior cohorts in engineering in the same regions, where men researchers increasingly have more productive collaborators compared to women. Throughout the EU28 and Japan, women authors tend to have slightly more senior collaborators compared to men. The largest gaps between men and women are found in Engineering in EU28, Japan, and Brazil, and B&E in Japan.

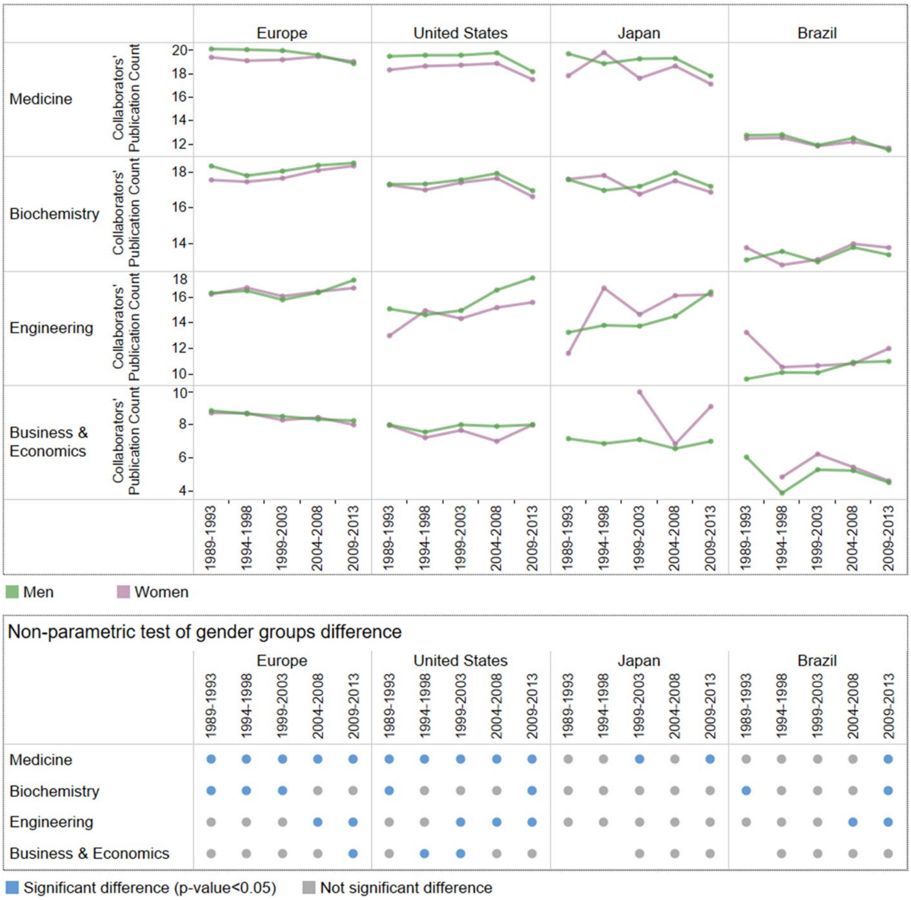

Fig. 4 *Above panel*: Median (by subgroup) of focal authors' first-order collaborators' publication count (mean). Subjects and regions are ordered from top to bottom and left to right, respectively, according to descending author count. Average values corresponding to fewer than 10 observations have been excluded from the analysis. Y-axis scales vary by subject. X-axis displays cohorts by region. *Below panel:* Significance of Wilcoxon Rank Sum test of difference between the two gender groups in each subject-region-cohort. Source: Scopus

Gender differences in span: interdisciplinary and international reach

Finally, we assess gender differences in spanning ties by analyzing the interdisciplinary and international reach of our focal authors. Compared to gender differences in status measures, we find more similarity with respect to interdisciplinary reach (defined as share of collaborations with co-authors publishing in different subject areas) and international reach, and a consistency across cohorts. Exceptions to this are men's consistently higher shares of interdisciplinary collaborators than women in medicine and biochemistry in the EU28 and USA, a trend echoed in several prior measures (Fig. 6). Further, in engineering in the USA, women have more interdisciplinary collaborators than men.

With the exception of EU28, our data show that men and women authors have similar international reach, across cohort, subject, and region (Fig. 7). In the EU28, we find

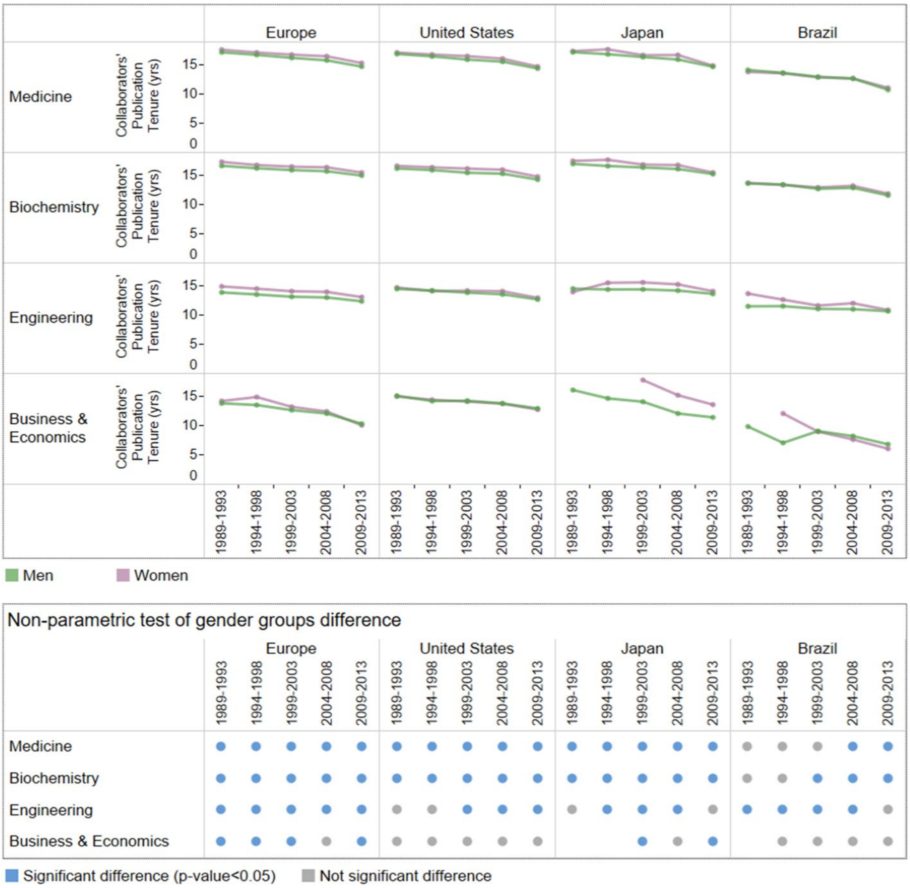

Fig. 5 *Above panel*: Median (by subgroup) of first-order collaborators' publication tenure (mean in years). Subjects and regions are ordered from top to bottom and left to right, respectively, according to descending author count. Average values corresponding to fewer than 10 observations have been excluded from the analysis. X-axis displays cohorts by region. *Below panel*: Significance of Wilcoxon Rank Sum test of difference between the two gender groups in each subject-region-cohort. Source: Scopus

significantly lower levels of median international reach among women in Medicine, Biochemistry, and Engineering across all cohorts, and in B&E among the more junior cohorts. We also find evidence of slightly lower levels of international collaboration for women in Medicine in Brazil. We also find that researchers with longer publication histories are characterized by higher median international reach, across subjects and regions.

Scientific collaboration is an increasingly global and cross-disciplinary endeavor, and with the exception of the EU28 and USA—where some lingering disparities are revealed—the general takeaway is positive for women compared to men in science with respect to cross-discipline, cross-region collaboration.

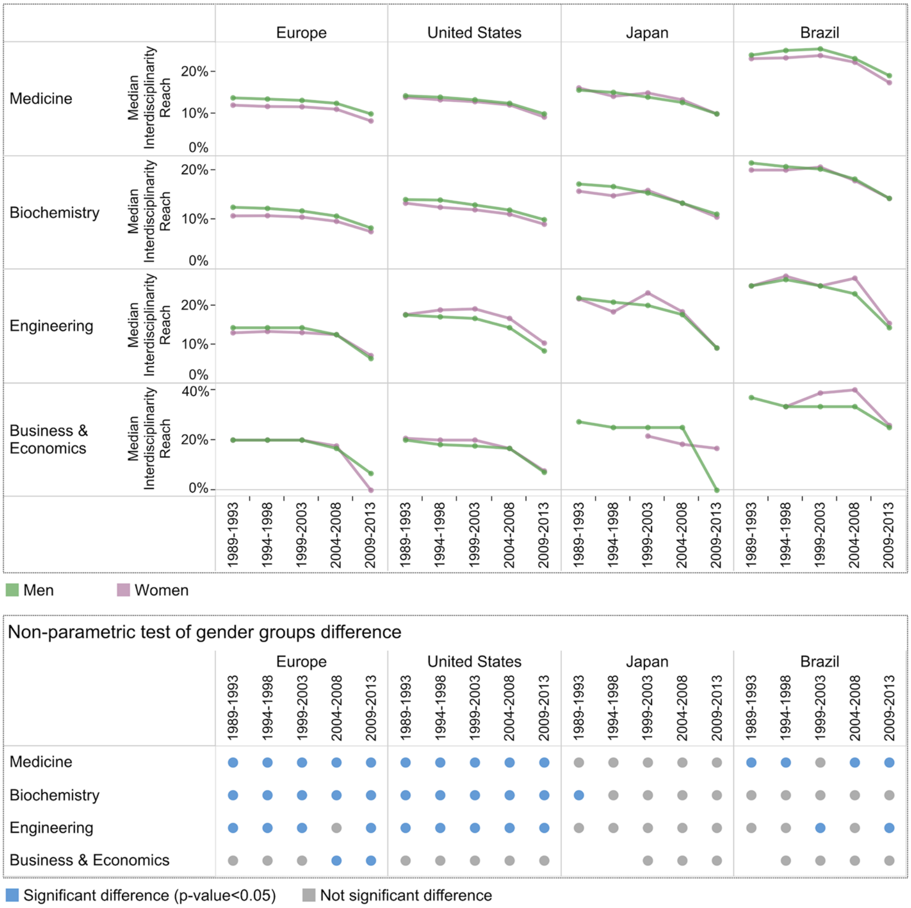

Fig. 6 *Above panel*: Median (by subgroup) interdisciplinary reach. Subjects and regions are ordered from top to bottom and left to right, respectively, according to descending author count. Average values corresponding to fewer than 10 observations have been excluded from the analysis. Y-axis scales vary by subject. X-axis displays cohorts by region. *Below panel:* Significance of Wilcoxon Rank Sum test of difference between the two gender groups in each subject-region-cohort. Source: Scopus

Discussion

Gender equality is important not only because it reflects the values of individuals within institutions, but also because it benefits the enterprise of science itself (Nielsen et al., 2017). Understanding men's and women's positioning in the network structure of scientific collaboration is key to understanding the social production of knowledge. Research ties facilitate links to additional contacts, assist the diffusion of emergent knowledge streams, and can provide scientists with access to new research opportunities across institutional, disciplinary, and geographic boundaries (Singh & Fleming, 2010; Inoue & Liu, 2015).

This research applies network analysis to an international corpus of publication data. We zero in on focal authors from a single year (2013) and examine collaborative activities across a 5-year window (2009–2013). Studying collaboration using network analysis allows us to examine the interaction between an author's characteristics and those of their

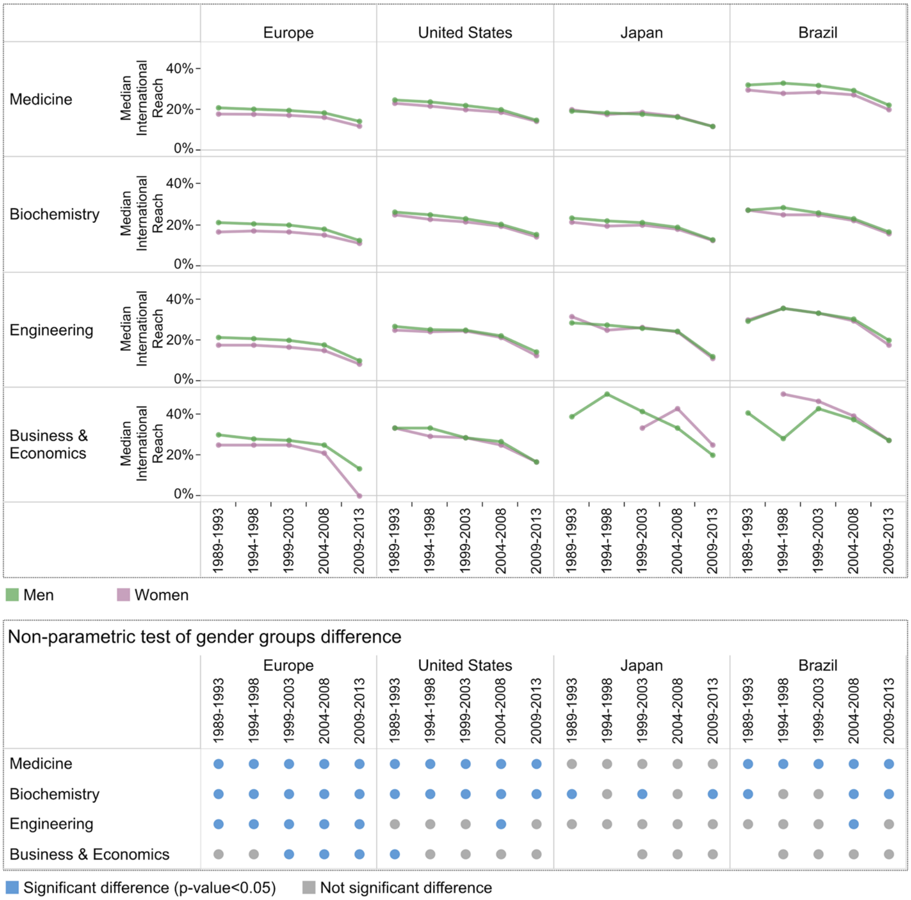

Fig. 7 *Above panel:* International reach (median by subgroup). Subjects and regions are ordered from top to bottom and left to right, respectively, according to descending author count. Average values corresponding to fewer than 10 observations have been excluded from the analysis. X-axis displays cohorts by region. *Below panel:* Significance of Wilcoxon Rank Sum test of difference between the two gender groups in each subject-region-cohort. Source: Scopus

co-authors, by looking at the relationship between the *structural* features of an author's co-authors, as well as co-author *status* (i.e., the co-author's demographic characteristics, experience, etc.) and their network *span* (interdisciplinary and international reach of their collaborations). These exploratory statistics reveal characteristics of men's and women's collaboration during this time in four subjects (Medicine, Biochemistry, Engineering, and Business and Economics) in the four regions of the EU28, the USA, Japan, and Brazil. In contrast to previous work, our network analysis is able to consider both interdisciplinary and international variation in gender-based differences in scientific collaboration.

Review of key findings

We find a gap in both focal authors' average productivity and publication tenure by gender (Table A.2), as well as consistent evidence of women's lower first-order degree centrality. The largest gaps in first-order degree centrality between men and women exist among the most senior cohort of authors: this gap shrinks across cohorts but remains across most region-subject pairs (Fig. 1). While women have fewer publications and collaborators than their men colleagues, their co-authors are equally resourced, holding similar levels of connections to the co-authors of men (Fig. 2). We also find that men and women tend to have co-authors with similar average productivity levels across subjects and regions, with a few exceptions (Fig. 4). Collaborator tenure is also largely similar, with women in the EU28 and Japan collaborating with others with slightly more experience (Fig. 5). There are several potential mechanisms that may drive the slight difference in connection to more senior collaborators, including differential positioning in roles or job tasks in collaborative space compared to men, disparate publishing trends by gender based on external forces, status-level processes that encourage the bifurcation of production roles in science, or growing levels of representation of women across fields (King & Frederickson, 2021; Macaluso et al., 2016; Milojević et al., 2018; West et al., 2013). Collectively, these findings are notable in that they contradict arguments that men would have higher-status collaborators (Cech, 2022; Moss-Racusin et al., 2012). We would expect high-status connections to be those that are highly productive; thus men, who are more likely to self-report having a high status connection (Elsevier, 2020a), should have collaborators with a higher average number of publications. But we find this is not the case.

We find many region-subject pairs to exhibit gender parity in the degree to which scholars pursue interdisciplinary research, with some exceptions (Fig. 6). In Medicine and Biochemistry in the USA and EU28, women have less interdisciplinary reach than men. The same is true in Engineering in the EU28, but in the USA, women have greater interdisciplinary reach. Many region-subject pairs also exhibit gender parity in international reach (Fig. 7). With the exception of EU28, our data show that men and women authors have similar international reach, across cohort, discipline, and geography. In the EU28, we find significantly lower levels of median international reach among women in Medicine, Biochemistry, and Engineering across all cohorts, and in B&E among the more junior cohorts.

These findings add additional evidence to research seeking deeper treatment of the ways in which men and women evidence interdisciplinarity (Rhoten & Pfirman, 2007; Sugimoto & Weingart, 2015) or engage with researchers internationally (Uhly et al., 2017; Zippel, 2017). Broadly, we find considerable parity in men's and women's engagement with international and interdisciplinary team collaboration. Yet the small significant gaps in the EU28 and USA—where women do lag in terms of interdisciplinary and international reach—help define scope conditions on which regions and subject areas may be in need of research attention. For these regions, the results are consistent with established work showing that gendered patterns of authorship and attribution reflect differences in specialization (Leahey, 2006, 2007; Leahey et al., 2008) and may have implications for career outcomes. Women academics tend to specialize less than men academics, thereby reducing their average visibility, productivity, and earnings (Leahey, 2006, 2007; Leahey et al., 2008). That said, we employ a single measure of cross-subject interaction, and a more sophisticated approach could build on this to consider multiple measures or a "framework" of interdisciplinarity (Digital Science et al., 2016). Our findings introduce new questions about the mechanisms that lead to cross-discipline and cross-region collaborations, and the ways in which men and women may be rewarded (or not) for these ties. Existing work suggests that articles authored by women in international collaborations receive fewer citations than those authored by men (Larivière et al., 2013).

Attention to structural position in collaboration has never been more relevant, as sole-authorship continues to decline and team science approaches are on the rise (Wuchty et al., 2007). Co-authorship connections are often driven by status inclusion and exclusion processes (i.e. conscious or unconscious decisions to seek out gender-similar collaborators (Whittington, 2018)). Perhaps the most dramatic gap we find across the set is that of gender homophily in the tendency to collaborate (Fig. 3). Homophily operates across all regions and all subject areas. Such preferences have implications for women's downstream research productivity, both for their inclusion as co-authors with men and especially where the representation of women is limited (e.g., there are fewer women than men to invite for collaboration). Homophily remains an organizing mechanism even when gender is more balanced in a field (Wang et al., 2019). However, the presence of durable homophilous relationship dynamics across contexts holds special implications for the importance of women's representation in regions and/or disciplines where their numbers are small. Relatedly, the propensity to seek out collaboration within, as opposed to across, gender boundaries has implications for those who focus on the value of diversity in group endeavors and potentially for the diversity of the scientific questions asked (Koning et al., 2021; Page, 2008; Jones et al., 2008; Etzkowitz et al., 1994; Nielsen et al., 2017).

Implications for global science

Looking across countries, we find trends that indicate larger gender gaps favoring men in first- and second-order degree centrality, international reach, and interdisciplinary reach in Medicine and Biochemistry in both the EU28 and the US. This is revealing, and on the surface puzzling, given the notably high representation of women in these fields in regions with comparatively high levels of gender equity. After all, prior research has shown women's scientific impact and output to be positively correlated with a nation's gender equity indicators (Chan & Torgler, 2020; Larivière et al., 2015). In our results, women in Medicine and Biochemistry in the EU28 and USA enjoy high average scientific output (see Online Resource 2). More generally, these findings raise questions about region-subject pairs where more progressive gender norms and an increased representation of women are presumed to lead to more gender-equitable career outcomes. However, our findings are consistent with work that finds less gender equality in STEM representation among countries with more progressive gender norms (Charles, 2011).

There are some possible explanations that may shed light on how to reconcile our findings with both strands of prior work. Charles and Bradley (2009) suggest that culturally-specific, normative influences may lead gender-differentiated STEM pathways to flourish in places where women's access to STEM education is high, and they find this to be the case with respect to women's choice of major in higher education. In science, disciplines and countries with ample opportunities for women may also introduce opportunities for gender differentiated career pathways and career positioning to emerge over time. In the USA and EU28 in particular, research in the life sciences encompasses an extremely diverse set of fields that can accommodate a plethora of career paths and engagement in research across academic, industrial, and clinic-based work (Powell et al., 2005; Smith-Doerr, 2004; Whittington, 2018). Fields and geographies where STEM labor supply is populous and in high demand may be more likely to develop various and differentiated career paths and positions and lead to gendered pathways in women's participation and involvement in the field. We suggest that in region-subject pairs where women's representation is high (i.e. the life sciences in the USA and EU28), culturally-specific, normative influences may also work to shape men's and women's network positioning. In region-subject pairs where women are making significant inroads into an area—such as the professions of medicine, and the life sciences in the USA and UK—research has found that gender-differentiated career pathways can develop inequity in men's and women's authority and responsibility (Goldin, 2014; Smith-Doerr, 2004; Whittington, 2009; Whittington & Smith-Doerr, 2005; Williams et al., 2013), with implications for overall levels of horizontal and vertical occupational sex segregation (Charles & Grusky, 2004). Flexibility and tracking in these fields may allow for increased, yet qualitatively different, participation among women scientists. In the case of authorship, women and men in these fields may be more likely to sort into career tracks and specialties that promote (or do not promote) publishing and collaborative research behavior. Women may be in the field, but in less advantageous network positions. It is important for future research to investigate these dynamics and their underlying mechanisms further.

Furthermore, parity in representation does not mean that women and men are afforded training opportunities with equal status. Weeden et al. (2017) find that although women earn nearly half of doctoral degrees in research fields, there is considerable gender segregation across fields in top-ranked, high-prestige PhD programs. That is, women in the USA and EU28 may be better represented in certain fields, but if they start their studies in lower-status PhD programs compared to men, this may set in motion a path of collaborative differences in authorship dynamics across their careers. Our data do not provide the details for us to more fully interrogate these dynamics, but future work would do well to investigate the mechanisms leading to geography- and field-specific differences in men's and women's career outcomes with more specificity.

Conclusion

Future research could broaden the scope of the existing measures and cohorts used and include more regions and subject areas. For example, the characteristics studied here are limited to the time window examined (and to those authors who published in 2013). Broadening the range of years to include more recent time periods alongside this set, and perhaps during the COVID-19 pandemic, could complement these findings and shed light on changes over time (and when men's and women's work-life balance is under stress). In addition to the network metrics examined here, future developments of this study could make use of more sophisticated (and more computationally intensive) metrics that a network analytic perspective can provide. These could include network measures that take into account a higher order of ties, such as power and closeness centrality (the extent to which authors connect to well-connected or powerful co-authors across a network, or sit on a short number of paths to others), the extent to which men and women act in brokerage capacities (connect otherwise unconnected co-authors, a frequent site for innovation), and the degree of overlap, clustering and aggregate constraint on men's and women's local network relationships.

Network-based indicators in this dataset could also be leveraged to examine whether and how men and women receive differential effects from co-authorship network position on research outcomes and career progression. Research has shown that women and men may have similar positioning, but receive differential benefits for this positioning (Whittington, 2018). It is important to assess whether and how these differences in influence may be in operation in co-authorship collaboration across subjects, regions, and time.

Our findings of gender differences and similarities in network positioning provide insight into the international and interdisciplinary structure of scholarly collaboration. Measures of the productivity and structure of these collaborations—including mean and median number of publications and first- and second-order degree centrality—gives us insight into inequalities in authors' positioning in the scholarly network. Measures of status provide understanding of how these relationships vary in their power and adherence to the network laws of preferential attachment, and thus in their influence over differential rewards to collaboration. Our results also find variation in gendered dynamics across geographical- and subject-space. A focus on variation across regions and subjects deepens our understanding of the relationship between region-level socio-economic context, opportunity and gender equity in science and provides important avenues for future research. Overall, our results enhance a broad understanding of gender differences across scholarly disciplines and geographies.

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Data availability The anonymized data of focal authors used in this analysis is available here: https://doi.org/10.17632/6vsbk97scn.1. The description of the data is as follows: This dataset includes author-level metrics for over 1.2 anonymized author profiles. The set of metrics measure the structure, status and span of the collaborative research activity of women and men authors active in four regions and four fields during the period 2009–2013.

References

Abramo, G., D'Angelo, C. A., & Di Costa, F. (2019a). The collaboration behavior of top scientists. *Scientometrics, 118*(1), 215–232.

Abramo, G., D'Angelo, C. A., & Di Costa, F. (2019b). A gender analysis of top scientists' collaboration behavior: Evidence from Italy. *Scientometrics, 120*, 405–418. https://doi.org/10.1007/s11192-019-03136-6

Abramo, G., D'Angelo, C. A., & Murgia, G. (2013). Gender differences in research collaboration. *Journal of Informetrics, 7*(4), 811–822.

Adams, J. (2013). The fourth age of research. *Nature, 497*, 557–560. https://doi.org/10.1038/497557a
Aksnes, D. W., Piro, F. N., & Rørstad, K. (2019). Gender gaps in international research collaboration: A bibliometric approach. *Scientometrics, 120*, 747–774. https://doi.org/10.1007/s11192-019-03155-3
Barabási, A. L., Jeong, H., Néda, Z., Ravasz, E., Schubert, A., & Vicsek, T. (2002). Evolution of the social network of scientific collaborations. *Physica a: Statistical Mechanics and Its Applications, 311*(3–4), 590–614.
Barjak, F., & Robinson, S. (2008). International collaboration, mobility and team diversity in the life sciences: Impact on research performance. *Social Geography, 3*(1), 23–36.
Bonacich, P. (1987). Power and centrality: A family of measures. *American Journal of Sociology, 92*(5), 1170–1182.
Boschini, A., & Sjögren, A. (2007). Is team formation gender neutral? Evidence from coauthorship patterns. *Journal of Labor Economics, 25*(2), 325–365.
Bozeman, B., & Corley, E. (2004). Scientists' collaboration strategies: Implications for scientific and technical human capital. *Research Policy, 33*(4), 599–616.
Bozeman, B., & Gaughan, M. (2011). How do men and women differ in research collaborations? An analysis of the collaborative motives and strategies of academic researchers. *Research Policy, 40*(10), 1393–1402.
Burt, R. S. (1998). The gender of social capital. *Rationality and Society, 10*(1), 5–46.
Burt, R. S. (2004). Structural holes and good ideas. *American Journal of Sociology, 110*(2), 349–399.
Cech, E. A. (2022). The intersectional privilege of white able-bodied heterosexual men in STEM. *Science Advances, 8*(24), eabo1558.
Ceci, S. J., & Williams, W. M. (2011). Understanding current causes of women's underrepresentation in science. *PNAS, 108*(8), 3157–3162.
Chan, H. F., & Torgler, B. (2020). Gender differences in performance of top cited scientists by field and country. *Scientometrics, 125*(3), 2421–2447.
Charles, M. (2011). What gender is science? *Contexts, 10*(2), 22–28.
Charles, M., & Bradley, K. (2009). Indulging our gendered selves? Sex segregation by field of study in 44 countries. *American Journal of Sociology, 114*(4), 924–976.
Charles, M., & Grusky, D. (2004). *Occupational Ghettos: Worldwide Segregation of Women and Men*. Stanford University Press.
Chinchilla-Rodríguez, Z., Miao, L., Murray, D., Robinson-García, N., Costas, R., & Sugimoto, C. R. (2018). A global comparison of scientific mobility and collaboration according to national scientific capacities. *Frontiers in Research Metrics and Analytics, 3*, 17.
Cole, J. R. (1987). *Fair Science: Women in the Scientific Community*. Columbia University Press.
Cole, J. R., & Zuckerman, H. (1984). The productivity puzzle. *Advances in Motivation and Achievement, 2*, 217–258.
Correll, S. J., Benard, S., & Paik, I. (2007). Getting a job: Is there a motherhood penalty? *American Journal of Sociology, 112*(5), 1297–1338.
Ding, W. W., Murray, F., & Stuart, T. E. (2006). Gender differences in patenting in the academic life sciences. *Science, 313*(5787), 665–667.
Elsevier (Kalamski, J. & Plume, A.). (2013, September). "Comparative Benchmarking of European and US Research Collaboration and Researcher Mobility." https://www.elsevier.com/__data/assets/pdf_file/0019/53074/Comparative-Benchmarking-of-European-and-US-Research-Collaboration-and-Researcher-Mobility_sept2013.pdf
Elsevier. (2017). Gender in the Global Research Landscape. https://www.elsevier.com/__data/assets/pdf_file/0008/265661/ElsevierGenderReport_final_for-web.pdf
Elsevier (De Kleijn, M., Jayabalasingham, B., Falk-Krzesinski, H. J., Collins, T., Kuiper-Hoyng, L., Cingolani, I., Zhang, J., Roberge, G., Goodall, A., Whittington, K. B., Berghmans, S. Huggett, S., & Tobin, S.) (2020a). The researcher journey through a gender lens: an examination of research participation, career progression and perceptions across the globe. https://www.elsevier.com/__data/assets/pdf_file/0011/1083971/Elsevier-gender-report-2020.pdf
Elsevier. (2020b). What are the most frequent Subject Area categories and classifications used in Scopus? https://service.elsevier.com/app/answers/detail/a_id/14882
Elsevier. (2020c). What is the complete list of Scopus Subject Areas and All Science Journal Classification Codes (ASJC)? https://service.elsevier.com/app/answers/detail/a_id/15181/
Etzkowitz, H., Kemelgor, C., Neuschatz, M., Uzzi, B., & Alonzo, J. (1994). The paradox of critical mass for women in science. *Science, 266*(5182), 51–54.
European Commission (EC). (2019). *She Figures 2018*. Publications Office of the European Union. https://op.europa.eu/s/oahv
Ferber, M. A. (1988). Citations and networking. *Gender & Society, 2*(1), 82–89.

Ferber, M. A., & Brün, M. (2011). The gender gap in citations: Does it persist? *Feminist Economics, 17*(1), 151–158.
Finkelstein, M. J., Conley, V. M., & Schuster, J. H. (2016). Taking the measure of faculty diversity. *Advancing Higher Education, 1*(4), 13.
Fox, M. F. (2001). Women, science, and academia: Graduate education and careers. *Gender & Society, 15*(5), 654–666.
Fox, M. F. (2005). Gender, family characteristics, and publication productivity among scientists. *Social Studies of Science, 35*(1), 131–150.
Fox, M. F. (2020). Gender, science, and academic rank: Key issues and approaches. *Quantitative Science Studies, 1*(3), 1001–1006.
Fox, M. F., & Freeman, J. (1989). Women and higher education: Gender differences in students and scholars. In J. Freeman (Ed.), *Women: A feminist perspective.* Mayfield.
Fox, M. F., & Mohapatra, S. (2007). Social-organizational characteristics of work and publication productivity among academic scientists in doctoral-granting departments. *The Journal of Higher Education, 78*(5), 542–571.
Fox, M. F., & Nikivincze, I. (2021). Being highly prolific in academic science: Characteristics of individuals and their departments. *Higher Education, 81*(6), 1237–1255.
Fox, M. F., Realff, M. L., Rueda, D. R., & Morn, J. (2017a). International research collaboration among women engineers: Frequency and perceived barriers, by regions. *The Journal of Technology Transfer, 42*(6), 1292–1306.
Fox, M. F., Whittington, K. B., & Linkova, M. (2017b). Gender, Inequity, and the Scientific Workforce. In U. Felt, R. Fouche, C. A. Miller, & L. Smith-Doerr (Eds.), *Handbook of Science and Technology Studies.* MIT Press.
Frehill, L. M., Vlaicu, S., & Zippel, K. (2010). *International scientific collaboration: Findings from a study of NSF principal investigators.* National Science Foundation.
Gaughan, M., & Bozeman, B. (2016). Using the prisms of gender and rank to interpret research collaboration power dynamics. *Social Studies of Science, 46*(4), 536–558.
Gazni, A., Sugimoto, C. R., & Didegah, F. (2012). Mapping world scientific collaboration: Authors, institutions, and countries. *Journal of the American Society for Information Science and Technology, 63*(2), 323–335.
Ghiasi, G., Larivière, V., & Sugimoto, C. R. (2015). On the compliance of women engineers with a gendered scientific system. *PLoS ONE, 10*(12), e0145931.
Goldin, C. (2014). A grand gender convergence: Its last chapter. *American Economic Review, 104*(4), 1091–1119.
Gould, R. V. (2002). The origins of status hierarchies: A formal theory and empirical test. *American Journal of Sociology, 107*(5), 1143–1178.
Granovetter, M. S. (1973). The strength of weak ties. *American Journal of Sociology, 78*(6), 1360–1380. https://doi.org/10.1086/225469
Haghani, M., Abbasi, A., Zwack, C. C., Shahhoseini, Z., & Haslam, N. (2022). Trends of research productivity across author gender and research fields: A multidisciplinary and multi-country observational study. *PLoS ONE, 17*(8), e0271998.
Hansen, M. T. (1999). The search-transfer problem: The role of weak ties in sharing knowledge across organization subunits. *Administrative Science Quarterly, 44*(1), 82–111.
Holman, L., & Morandin, C. (2019). Researchers collaborate with same-gendered colleagues more often than expected across the life sciences. *PLoS ONE, 14*(4), e0216128.
Holman, L., Stuart-Fox, D., & Hauser, C. E. (2018). The gender gap in science: How long until women are equally represented? *PLoS Biology, 16*(4), e2004956.
Huang, J., Gates, A. J., Sinatra, R., & Barabási, A.-L. (2020). Historical comparison of gender inequality in scientific careers across countries and disciplines. *Proceedings of the National Academy of Sciences, 117*(9), 4609–4616. https://doi.org/10.1073/pnas.1914221117
Hunter, L., & Leahey, E. (2008). Collaborative research in sociology: Trends and contributing factors. *The American Sociologist, 39*(4), 290–306. https://doi.org/10.1007/s12108-008-9042-1
Hunter, L. A., & Leahey, E. (2010). Parenting and research productivity: New evidence and methods. *Social Studies of Science, 40*(3), 433–451.
Ibarra, H. (1992). Homophily and differential returns: Sex differences in network structure and access in an advertising firm. *Administrative Science Quarterly, 37*, 422–447.
Ibarra, H. (1997). Paving an alternative route: Gender differences in managerial networks. *Social Psychology Quarterly, 60*, 91–102.
Inoue, H., & Liu, Y. Y. (2015). Revealing the intricate effect of collaboration on innovation. *PLoS ONE, 10*(3), e0121973.

Jeong, H., Néda, Z., & Barabási, A. L. (2003). Measuring preferential attachment in evolving networks. *EPL (Europhysics Letters), 61*(4), 567.
Jones, B. F., Wuchty, S., & Uzzi, B. (2008). Multi-university research teams: Shifting impact, geography, and stratification in science. *Science, 322*(5905), 1259–1262.
King, M. M., Bergstrom, C. T., Correll, S. J., Jacquet, J., & West, J. D. (2017). Men set their own cites high: Gender and self-citation across fields and over time. *Socius, 3*, 2378023117738903.
King, M. M., & Frederickson, M. E. (2021). The pandemic penalty: The gendered effects of COVID-19 on scientific productivity. *Socius, 7*, 23780231211006976.
Kiopa, A., Melkers, J., & Tanyildiz, Z. E. (2009). Women in academic science: Mentors and career development. In K. Prpić, L. Oliveira, & S. Hemlin (Eds.), *Women in Science and Technology* (pp. 55–84). Institute for Social Research.
Knobloch-Westerwick, S., Glynn, C. J., & Huge, M. (2013). The Matilda effect in science communication: An experiment on gender bias in publication quality perceptions and collaboration interest. *Science Communication, 35*(5), 603–625.
Koning, R., Samila, S., & Ferguson, J. P. (2021). Who do we invent for? Patents by women focus more on women's health, but few women get to invent. *Science, 372*(6548), 1345–1348.
Kwiek, M., & Roszka, W. (2021). Gender disparities in international research collaboration: A study of 25,000 university professors. *Journal of Economic Surveys, 35*(5), 1344–1380.
Kyvik, S., & Teigen, M. (1996). Child care, research collaboration, and gender differences in scientific productivity. *Science, Technology, & Human Values, 21*(1), 54–71.
Larivière, V., Gingras, Y., Sugimoto, C. R., & Tsou, A. (2015). Team size matters: Collaboration and scientific impact since 1900. *Journal of the Association for Information Science and Technology, 66*(7), 1323–1332.
Larivière, V., Ni, C., Gingras, Y., Cronin, B., & Sugimoto, C. R. (2013). Bibliometrics: Global gender disparities in science. *Nature, 504*(7479), 211–213.
Larivière, V., Vignola-Gagné, E., Villeneuve, C., Gélinas, P., & Gingras, Y. (2011). Sex differences in research funding, productivity and impact: An analysis of Québec university professors. *Scientometrics, 87*(3), 483–498.
Leahey, E. (2006). Gender differences in productivity: Research specialization as a missing link. *Gender & Society, 20*(6), 754–780.
Leahey, E. (2007). Not by productivity alone: How visibility and specialization contribute to academic earnings. *American Sociological Review, 72*(4), 533–561.
Leahey, E. (2016). From sole investigator to team scientist: Trends in the practice and study of research collaboration. *Annual Review of Sociology, 42*, 81–100.
Leahey, E., Crockett, J. L., & Hunter, L. A. (2008). Gendered academic careers: Specializing for success? *Social Forces, 86*(3), 1273–1309.
Lee, S., & Bozeman, B. (2005). The impact of research collaboration on scientific productivity. *Social Studies of Science, 35*(5), 673–702.
Leifer, E. M. (1988). Interaction preludes to role setting: Exploratory local action. *American Sociological Review, 53*(6), 865–878.
Ley, T. J., & Hamilton, B. H. (2008). The gender gap in NIH grant applications. *Science, 322*(5907), 1472–1474.
Lockhart, J. W., King, M. M., & Munsch, C. (2023). Name-based demographic inference and the unequal distribution of misrecognition. *Nature Human Behavior, 7*, 1084–1095.
Long, J. S., & Fox, M. F. (1995). Scientific careers: Universalism and particularism. *Annual Review of Sociology, 21*, 45–71.
Macaluso, B., Larivière, V., Sugimoto, T., & Sugimoto, C. R. (2016). Is science built on the shoulders of women? A study of gender differences in contributorship. *Academic Medicine, 91*(8), 1136–1142.
Madlock-Brown, C., & Eichmann, D. (2016, August). The scientometrics of successful women in science. In *2016 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining (ASONAM)* (pp. 654–660). IEEE.
Marsh, H. W., Bornmann, L., Mutz, R., Daniel, H.-D., & O'Mara, A. (2009). Gender effects in the peer reviews of grant proposals: A comprehensive meta-analysis comparing traditional and multilevel approaches. *Review of Educational Research, 79*(3), 1290–1326.
Mason, M. A., Wolfinger, N. H., & Goulden, M. (2013). *Do babies matter?: Gender and family in the ivory tower*. Rutgers University Press.
McDowell, J. M., & Smith, J. K. (1992). The effect of gender-sorting on propensity to coauthor: Implications for academic promotion. *Economic Inquiry, 30*(1), 68–82.
McPherson, M., Smith-Lovin, L., & Cook, J. M. (2001). Birds of a feather: Homophily in social networks. *Annual Review of Sociology, 27*, 415–444.

Meng, Y. (2016). Collaboration patterns and patenting: Exploring gender distinctions. *Research Policy, 45*(1), 56–67.
Milojević, S., Radicchi, F., & Walsh, J. P. (2018). Changing demographics of scientific careers: The rise of the temporary workforce. *Proceedings of the National Academy of Sciences, 115*(50), 12616–12623.
Moss-Racusin, C. A., Dovidio, J. F., Brescoll, V. L., Graham, M. J., & Handelsman, J. (2012). Science faculty's subtle gender biases favor male students. *Proceedings of the National Academy of Sciences, 109*(41), 16474–16479.
Moss K. R. (1977). *Men and Women of the Corporation*. Basic Books, New York.
National Science Foundation (NSF). (2004). *Gender Differences in the Careers of Academic Scientists and Engineers: A Literature Review*. NSF Division of Science Resources Statistics. http://www.nsf.gov/statistics/nsf03322/pdf/front.pdf
National Academy of Sciences. (2005). *Facilitating Interdisciplinary Research*. National Academies Press.
National Academy of Sciences. (2007). *Beyond Bias and Barriers: Fulfilling the Potential of Women in Academic Science and Engineering*. National Academies Press. https://doi.org/10.17226/11741
National Research Council. (2001). *From scarcity to visibility: Gender differences in the careers of doctoral scientists and engineers*. National Academies Press. https://doi.org/10.17226/5363
Nielsen, M. W., Alegria, S., Börjeson, L., Etzkowitz, H., Falk-Krzesinski, H. J., Joshi, A., Leahey, E., Smith-Doerr, L., Woolley, A. W., & Schiebinger, L. (2017). Gender diversity leads to better science. *Proceedings of the National Academy of Sciences, 114*(8), 1740–1742.
Ozel, B., Kretschmer, H., & Kretschmer, T. (2014). Co-authorship pair distribution patterns by gender. *Scientometrics, 98*(1), 703–723.
Page, S. (2008). *The difference: How the power of diversity creates better groups, firms, schools, and societies-new edition*. Princeton University Press.
Powell, W. W., White, D. R., Koput, K. W., & Owen-Smith, J. (2005). Network dynamics and field evolution: The growth of interorganizational collaboration in the life sciences. *American Journal of Sociology, 110*(4), 1132–1205.
Rhoten, D., & Pfirman, S. (2007). Women in interdisciplinary science: Exploring preferences and consequences. *Research Policy, 36*(1), 56–75. https://doi.org/10.1016/j.respol.2006.08.001
Ridgeway, C. L. (2011). *Framed by gender: How gender inequality persists in the modern world*. Oxford University Press.
Rossiter, M. W. (1993). The matthew matilda effect in science. *Social Studies of Science, 23*(2), 325–341. https://doi.org/10.1177/030631293023002004
Sands, R. G., Parson, L. A., & Duane, J. (1991). Faculty mentoring faculty in a public university. *The Journal of Higher Education, 62*(2), 174–193.
Schiebinger, L. (2001). Women and science: Why does it matter. In A. Colosimo, B. Degan, & N. Dewandre (Eds.), *Women and science: Making change happen* (pp. 16–25). European Commission.
Science, D., Adams, J., Loach, T., & Szomszor, M. (2016). Digital Research Report: Interdisciplinary research—Methodologies for identification and assessment. Digital Science. https://doi.org/10.6084/m9.figshare.4270289.v1
Shen, H. (2013). Inequality quantified: Mind the gender gap. *Nature News, 495*(7439), 22.
Singh, J., & Fleming, L. (2010). Lone inventors as sources of breakthroughs: Myth or reality? *Management Science, 56*(1), 41–56.
Smith-Doerr, L. (2004). *Women's work: Gender equality vs. hierarchy in the life sciences*. Lynne Rienner Publishers.
Smith-Lovin, L., & McPherson, J. M. (1993). You are who you know: A network approach to gender. In P. England (Ed.), *Theory on gender, feminism on theory* (pp. 223–241). Aldine de Gruyter.
Sugimoto, C. R., Sugimoto, T. J., Tsou, A., Milojević, S., & Larivière, V. (2016). Age stratification and cohort effects in scholarly communication: A study of social sciences. *Scientometrics, 109*(2), 997–1016. https://doi.org/10.1007/s11192-016-2087-y
Sugimoto, C. R., & Weingart, S. (2015). The kaleidoscope of disciplinarity. *Journal of Documentation, 71*(4), 775–794.
Uhly, K. M., Visser, L. M., & Zippel, K. S. (2017). Gendered patterns in international research collaborations in Academia. *Studies in Higher Education, 42*(4), 760–782. https://doi.org/10.1080/03075079.2015.1072151
Wagner, C. S., & Leydesdorff, L. (2005). Network structure, self-organization, and the growth of international collaboration in Science. *Research Policy, 34*(10), 1608–1618. https://doi.org/10.1016/j.respol.2005.08.002
Wang, Y. S., Lee, C. J., West, J. D., Bergstrom, C. T., & Erosheva, E. A. (2019). Gender-based homophily in collaborations across a heterogeneous scholarly landscape. *arXiv preprint* arXiv:1909.01284.

Wang, Q., & Schneider, J. W. (2020). Consistency and validity of interdisciplinarity measures. *Quantitative Science Studies, 1*(1), 239–263. https://doi.org/10.1162/qss_a_00011
Weeden, K. A., Thébaud, S., & Gelbgiser, D. (2017). Degrees of Difference: Gender Segregation of U.S. Doctorates by Field and Program Prestige. *Sociological Science, 4*(6), 123–150.
West, J. D., Jacquet, J., King, M. M., Correll, S. J., & Bergstrom, C. T. (2013). The role of gender in scholarly authorship. *PLoS ONE, 8*(7), e66212. https://doi.org/10.1371/journal.pone.0066212
Whittington, K. B. (2009). Patterns of male and female scientific dissemination in public and private science. In R. B. Freeman & D. L. Goroff (Eds.), *Science and engineering careers in the United States: An analysis of markets and employment* (pp. 195–228). University of Chicago Press. https://doi.org/10.7208/chicago/9780226261904.003.0007
Whittington, K. B. (2011). Mothers of invention? *Work and Occupations, 38*(3), 417–456. https://doi.org/10.1177/0730888411414529
Whittington, K. B. (2018). A tie is a tie? Gender and network positioning in life science inventor collaboration. *Research Policy, 47*(2), 511–526. https://doi.org/10.1016/j.respol.2017.12.006
Whittington, K. B., & Smith-Doerr, L. (2005). Gender and commercial science: Women's patenting in the life sciences. *The Journal of Technology Transfer, 30*(4), 355–370. https://doi.org/10.1007/s10961-005-2581-5
Williams, J. C., Blair-Loy, M., & Berdahl, J. L. (2013). Cultural schemas, social class, and the flexibility stigma. *Journal of Social Issues, 69*(2), 209–234. https://doi.org/10.1111/josi.12012
World Economic Forum. (2020). *Global Gender Gap Report 2020*. https://www.weforum.org/reports/gender-gap-2020-report-100-years-pay-equality
Wuchty, S., Jones, B. F., & Uzzi, B. (2007). The increasing dominance of teams in production of knowledge. *Science, 316*(5827), 1036–1039. https://doi.org/10.1126/science.1136099
Xie, Y., & Shauman, K. A. (1998). Sex differences in research productivity: New evidence about an old puzzle. *American Sociological Review, 63*(6), 847. https://doi.org/10.2307/2657505
Xie, Y., & Shauman, K. A. (2003). *Women in science: Career processes and outcomes*. Harvard University.
Zeng, X. H., Duch, J., Sales-Pardo, M., Moreira, J. A., Radicchi, F., Ribeiro, H. V., Woodruff, T. K., & Amaral, L. A. (2016). Differences in collaboration patterns across discipline, career stage, and gender. *Plos Biology*. https://doi.org/10.1371/journal.pbio.1002573
Zippel, K. (2017). Women in global science. *Stanford University Press*. https://doi.org/10.1515/9781503601505