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The Pandemic Penalty: The Gendered Effects of COVID-19 on Scientific Productivity

Molly M. King¹ and Megan E. Frederickson²

Abstract

Academia serves as a valuable case for studying the effects of social forces on workplace productivity, using a concrete measure of output: scholarly papers. Many academics, especially women, have experienced unprecedented challenges to scholarly productivity during the coronavirus disease 2019 (COVID-19) pandemic. The authors analyze the gender composition of more than 450,000 authorships in the arXiv and bioRxiv scholarly preprint repositories from before and during the COVID-19 pandemic. This analysis reveals that the underrepresentation of women scientists in the last authorship position necessary for retention and promotion in the sciences is growing more inequitable. The authors find differences between the arXiv and bioRxiv repositories in how gender affects first, middle, and sole authorship submission rates before and during the pandemic. A review of existing research and theory outlines potential mechanisms underlying this widening gender gap in productivity during COVID-19. The authors aggregate recommendations for institutional change that could ameliorate challenges to women's productivity during the pandemic and beyond.

Keywords

gender, publication, COVID-19, pandemic, authorship, careers, sociology of science

The coronavirus disease 2019 (COVID-19) pandemic has caused myriad social changes throughout society, including in the academy. Reports of reduced productivity for faculty members, both anecdotal and data-driven, draw attention to the fact that the ivory tower is not immune from shocks to our most essential social systems. In fact, because of the clear metrics of productivity in faculty careers, academia makes for an excellent case study of how an exogenous shock affects institutional practices.

Many of these changes are disproportionately affecting the productivity of women academics.¹ Women academics have faced disproportionate work-life balance challenges during the pandemic and are more likely to have reduced their research hours than men (Deryugina, Shurchkov, and Stearns 2021; Myers et al. 2020). There are several possible reasons for this. Because the COVID-19 pandemic has resulted in widespread school and daycare closures, many academics are or have been working from home with their children underfoot. More likely to be in dual-academic

relationships, women scientists have fewer supports at home than men, who are more likely to have partners who do not work full-time for pay. At work, women faculty are likely to perform more service, exert more emotional labor, and spend more time transitioning to online learning. Our study contributes to the research base on women academics' reduced productivity during the COVID-19 pandemic by integrating data analysis of gender gaps in preprint submissions with a theoretical discussion of possible mechanisms for these differences.

We quantify the effects of these structural and societal changes on women's productivity by analyzing data on preprint submissions in STEM (science, technology, engineering, and math). Although there has been significant progress closing the gender gap in these fields, STEM remains one of the most gender unequal realms of the academy (Hill,

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¹We intentionally use *men* and *women* rather than *male* and *female* to refer to scholars' gender (as reflected by their names) rather than biological sex.



Corbett, and St. Rose 2010). Furthermore, scientific fields have power, authority, and status in our modern society—as do the scientists who work in them (Fox, Whittington, and Linkova 2017). The demographics of those who produce knowledge shape not only the knowledge that is produced (Campbell et al. 2013) but also the characteristics of people society views as powerful and important. The persistence of gender inequality in STEM is symbolically and materially representative of how social structures influence opportunities for professional women.

To analyze the effects of the societal changes wrought by the pandemic on scientific productivity, we examine arXiv and bioRxiv, two preprint servers that together cover most STEM fields, including biology, physics, math, computer science, and statistics, among others. A preprint is a version of an academic paper that is posted online for public consumption prior to or concurrent with the formal peer-review process. Several discipline-specific preprint repositories exist, and these play an important role in the dissemination of research (Berg et al. 2016; Freese and King 2018). Unlike manuscripts undergoing the peer-review process, preprints are posted online within a week of submission (and usually the next day) (arXiv 2021; bioRxiv 2021). Two thirds of bioRxiv preprints are published in peer-reviewed journals within two years (Abdill and Blekhman 2019). The prevalence of preprints is on the rise throughout many disciplines (Abdill and Blekhman 2019; Penfold and Polka 2020), and because peer review takes time, preprints may offer a better real-time measure of the pandemic's effect on academic productivity than published articles in scholarly journals. Preliminary evidence also suggests a growing importance for preprints during the pandemic, as there is a high demand for rapid research to understand COVID-19 (Fraser et al. 2020).

Understanding the effects of the pandemic on productivity is important because, despite substantial gains over the past few decades, women remain significantly underrepresented in faculty positions, particularly tenured positions (Snyder, de Brey, and Dillow 2019) and especially so in STEM fields (Burrelli 2008; Fox 2001). And more highly educated women in the United States are now becoming mothers than in the past, suggesting that the childcare crisis brought on by the pandemic may have widespread effects within academia; 80 percent of women with doctorates or professional degrees aged 40 and older are mothers, up from 65 percent only 20 years ago (Livingston 2018). Even before the pandemic, women were already more likely to leave full-time STEM employment after the birth of a first child (Cech and Blair-Loy 2019). Ignoring the disproportionate effects of the COVID-19 pandemic on women's productivity risks backsliding on substantial progress for academic diversity (Woolston 2020). In addition to being an institutional goal for many organizations, gender diversity can also increase scientific discovery and innovation (Nielsen et al. 2017).

We continue by reviewing why studying academic publishing during the pandemic provides a valuable case for analyzing shocks to social support. In a section on possible explanations, we review existing work on structural features of academia and households that might contribute to the productivity patterns we observe. Next, we analyze data from two preprint repositories to assess the gendered publication gap in STEM during the pandemic. We conclude with recommendations for university policy.

A Case Study in Shocks to Professional Support: Productivity during the Pandemic

Not only does the pandemic have the potential to affect the careers of a generation of scholars, it also provides an important natural experiment in the disruption of work-life routines that have been carefully designed to accommodate institutional demands. This dramatic shift in routine serves as an instrumental variable, allowing a unique view into the society-wide dynamics of work-life previously accessible only through shocks to individual lives (Newhouse and McClellan 1998).

The ongoing productivity of academics and other white-collar workers presumes a foundation of smoothly running care work and support in the home. This support system allows the “ideal worker” to work long hours without concern for family obligations (Misra, Lundquist, and Templer 2012). In other words, “the classic profile of an academic career is cut to the profile of the traditional man with his traditional wife” (Hochschild 1994:126). Those who deviate from this ideal (by choice or necessity) are challenged with unrealistic expectations for retention, tenure, or promotion (Misra et al. 2012). This penalty is most powerful for women but also affects men; traditional gender norms have negative effects on all modern families (Sallee 2012; Wayne and Cordeiro 2003).

Academic careers make a particularly valuable case study because the measurement of productivity is very clear compared with other white-collar professions. Publication is a concrete outcome with settled value in academia. Skipping even a single year of publication significantly reduces the citation impact of a highly productive scientist (Ioannidis, Boyack, and Klavans 2014). Analyzing preprint productivity provides insight into the challenges for this generation of academics and the institutional supports underlying the productivity of professionals.

Several analyses have already assessed the differential impact of the pandemic on men and women academics' productivity. An analysis in economics found decreases in submissions by women authors in March and April 2020 (Shurchkov, Deryugina, and Stearns 2020). A study of 40,000 preprints from the Social Science Research Network (SSRN) found that although total research productivity increased, women's productivity decreased relative to men's, and these effects were more pronounced among higher ranked

universities (Cui, Ding, and Zhu 2020). Another working paper analyzing the preprint repositories medRxiv and bioRxiv and select Springer-Nature journals showed a drop in women's relative publishing rates during the pandemic, exacerbated in less wealthy countries (Muric, Lerman, and Ferrara 2020). Another analysis of 1.2 million authors found the largest reductions in submissions by women in the National Bureau of Economic Research, SocArXiv, EarthArXiv, and medRxiv repositories. In contrast, preprint submissions by women first authors in arXiv and bioRxiv in March and April 2020 remained steady compared with both February 2020 and March and April 2019 (Vincent-Lamarre, Sugimoto, and Larivière 2020a). Analysis of 60,000 journals showed a 7 percentage point reduction in first authorships by women in May 2020 relative to 2019 (Matthews 2020). Additionally, studies have shown significant gender gaps in authorship on COVID-19-related research (Amano-Patiño et al. 2020; Andersen et al. 2020; Gabster et al. 2020; Pinho-Gomes et al. 2020). Only two discipline-specific analyses, in political science and ecology, showed no gendered decreases in productivity during the early pandemic (Dolan and Lawless 2020; Fox and Meyer 2021). Most of these studies were not yet peer reviewed at the time of writing, and many draw on limited data. Nonetheless, they provide insight into the gap in productivity that is to come. Analyses of preprints are warning signals as the challenges of working from home build up and differentially affect men and women.

Here, we add to these studies by extending analyses of the pandemic-affected period through the end of June 2020. This provides time for preprint outputs to reflect the effect of lockdown orders, which began in March 2020 in many parts of the world. These data also provide a glimpse into the summer season productivity gap of academics affected by ongoing institutional changes, discussed below.

We chose to quantify the effect of the COVID-19 pandemic on the gender breakdown of preprint submissions to arXiv and bioRxiv because they provide a broad sample of STEM fields, include very large numbers of preprints, and provide data in easily accessible formats. They also include fields that vary in authorship order conventions. Many authorships in the arXiv preprint repository are alphabetical by last name (including mathematics and economics), so we do not expect to see great discrepancies in our findings among author positions. In contrast, author order in the biological sciences lists the primary contributor first and the leader of the study and most senior author last (Waltman 2012). This last author position is key for promotion and tenure in the biosciences (Wren et al. 2007). Middle authors are understood to be those who have contributed the least to the paper (Larivière et al. 2016). Therefore, we expect to see variation in gender gaps by author order within the bioRxiv repository. Women have historically been underrepresented in the prestige positions of first and last authorship (West et al. 2013). Next, we discuss the reasons we expect to find gender disparities increasing as a result of the pandemic.

Possible Explanations

Gender scholars have documented substantial gender inequality in science and the academy. Although our analysis does not allow us to distinguish among explanations for the observed patterns, previous research on the mechanisms underlying gender gaps in productivity can help illuminate the trends we have observed in preprint authorships during the pandemic.²

Long before the COVID-19 pandemic, multiple studies assessed gender differences in research productivity among academics, with somewhat mixed results (Long 1992; Xie and Shauman 1998; Weisshaar 2017). Some studies found that the gender gap in productivity has decreased over time and disappeared in the youngest generation of researchers (van Arensbergen, van der Weijden, and van den Besselaar 2012), suggesting that academia had been making progress toward greater gender equity in publishing. However, women academics are still disproportionately responsible for childcare and household work, more likely to be in dual-career relationships with other academics, and have more service and teaching responsibilities, all of which disproportionately affect their research productivity.

Domestic Work and Childcare in the Pandemic

Many countries and states closed schools and childcare centers to slow the spread of COVID-19, such that 90 percent of the world's school-aged children were out of school on April 15, 2020, and some were still out of school through the start of 2021. As a result, many parents have been responsible for caring for, and often homeschooling, their children during the pandemic, often while simultaneously expected to work from home. A gender gap in time spent on childcare and domestic labor is thus one possible explanation for the

²Of course, there could be other possible mechanisms that explain the productivity gap, though we think these are less likely given the preponderance of the evidence. For example, perhaps there has been a surge in preprints from some fields, and those fields happened to have more men scholars in them. This is supported by the finding that although the proportion of women economists contributing to non-pandemic-related working paper submissions remains stable, women economists were not becoming involved in the new area of COVID-19 research at the same rate as men (Amano-Patiño et al. 2020). However, although epidemiology has seen a huge surge of preprint submissions, it is a field with relatively equal gender ratios of practitioners before the pandemic (Schisterman et al. 2017). Alternatively, women might be a part of the types of collaborations that are harder to carry out during COVID-19 restrictions. In a similar vein, if women are disproportionately represented in laboratory-based sciences relative to theoretical work (within a given field), they would find it harder to continue doing research during the pandemic (Myers et al. 2020). Or perhaps there are regional differences in the effect of COVID-19 on productivity that correlate with gender differences in scientific field composition.

growing gap in productivity during the pandemic. This is exacerbated by the tendency for women scientists to be partnered with another academic, while men scientists are more likely to have partners who do not work full-time for pay.

Domestic Work and Childcare. The proportion of parents who report sharing domestic chores equally has increased since before the pandemic. As a result, the fraction of families in which mothers are primarily responsible for household labor has decreased substantially. Nonetheless, more than one-quarter of mothers also report doing substantially more in both childcare and housework as a result of the shelter-at-home orders (Carlson, Petts, and Pepin 2020). The childcare burden is even greater for single parents, who in Canada, for example, make up 20 percent of families with children younger than 16. Women make up 81 percent of these single-parent householders (Statistics Canada 2015).

Women scientists, on average, are less likely to have full-time support at home, a trend that likely has been exacerbated by the pandemic. A 2008 survey found that men academics were four times more likely to have partners who do not work outside the home than were women academics (Schiebinger, Henderson, and Gilmartin 2008). Layoffs and furloughs due to the economic downturn associated with COVID-19 have disproportionately affected women (Alon et al. 2020; Cottom 2020). As a result, it is likely that even more men than the 20 percent reported (in 2008, when men were statistically more likely to be out of work) will currently have stay-at-home partners.

If anything, we expect that this disparity will only continue to increase as children stay home. When a couple is considering who might quit or reduce work hours to accommodate increased at-home childcare demands, even an ideologically egalitarian couple is more likely to choose the lower earner to stay home (Risman 1998).³ Nonacademic women partners may have voluntarily stayed home or reduced work hours more often than men during the pandemic (Alon et al. 2020; Kitchener 2020). A study using the U.S. Current Population Survey found that during the first outbreak of COVID-19, mothers with young children reduced their work hours four to five times more than fathers (Collins et al. 2020).

It has been suggested that because of historically greater levels of gender bias in faculty hiring, women academics may be younger on average than men academics and therefore more likely to have children at home during the COVID-19 pandemic (Matthews 2020). However, at least in the United States, men tenure-track professors are actually

more likely to have children living in the household than same-stage women.⁴ In the 2017 National Science Foundation Survey of Doctorate Recipients, 44.0 percent of men assistant professors reported having children in their households, compared with 40.0 percent of women assistant professors (NSF 2019). This gap remains consistent at the associate professor level, with 46.1 percent of men and 42.6 percent of women, and at the full professor rank, with 36.6 percent of men and 30.1 percent of women reporting children in the home. For instructors and lecturers, who are much more likely to be women, however, the reverse is true: 39.6 percent of women and 29.5 percent of men have children at home.⁵ However, instructors and lecturers are likely responsible for only a small number of preprint submissions, as their jobs focus primarily on teaching (although some still make important, but often unpaid, contributions to scientific research).

Because academic women typically have children fairly late into their child-bearing years (Mason and Goulden 2004), women principal investigators are more likely to have young children at home than women graduate students or postdocs. In the biological sciences, last authors are generally principal investigators who head up labs, while first authors are often graduate students or postdoctoral researchers. Therefore, in our bioRxiv data, we expect to see the greatest gender gaps among last authors. In the arXiv repository, we expect the same to hold in the fields of physics and computer science, in which senior authors are typically listed last, but not in mathematics, in which authors are generally listed alphabetically (Waltman 2012).

Women scientists are responsible for the majority of childcare responsibilities in the home (Schiebinger and Gilmartin 2010). Women do more than half of the childcare in their households, while men scientists are responsible for about a third. This is true across rank: there is little variation among younger generations of scholars (Schiebinger and Gilmartin 2010). Women faculty with children spend more than 15 more hours on caregiving activities per week than their men colleagues (Mason et al. 2005). Even among early-career physician-researchers funded by the National Institutes of Health who have children, women reported spending 8.5 more hours per week on domestic work than men, controlling for spousal employment and work hours (Jolly et al. 2014). A survey of academic scientists at research

³The work that gets prioritized is the work that provides the core financial stability for the household. Because women are statistically more likely to be the lower earner, this implies that women's productivity may be deprioritized. However, this consideration of a spouse's income in deciding who will quit affects only women's decisions to leave the labor force (Cha 2010).

⁴This is in part because women with children are more likely to leave academia early in their careers (Mason, Wolfinger, and Goulden 2013).

⁵We generated these summary statistics using the publicly available 2017 National Science Foundation Survey of Doctorate Recipients on the Scientists and Engineers Statistical Data System (NSF 2019). The results of this tabulation are available on the Open Science Framework repository for the project (<https://osf.io/upt7y/>). This table details whether the respondent has children living in the household, split by job position and gender.

institutions revealed that although both men and women report that work interferes with family more than the reverse, women report more conflict in both directions (Fox, Fonseca, and Bao 2011). As a result, in dual-earner couples, women academics are more likely than men academics to be responsible for a majority of the household work (Schiebinger and Gilmartin 2010). Furthermore, all these studies were conducted before the COVID-19 pandemic, when parents could avail themselves of “normal” childcare options.

Impact of Children on Research Productivity. Prepandemic findings on the effects of children on academic productivity have been mixed, though the most recent studies show a negative effect of having (especially young) children at home on women’s research productivity. Women researchers with young children are less productive than both their men and child-free women colleagues after controlling for other structural factors such as research funding and collaboration (Kyvik and Teigen 1996). Although one study showed that women scientists with preschool-age children are more productive than either women with school-age children or women without children, these effects disappear after controlling for other significant predictors of productivity, such as advising responsibilities and interest in research (Fox 2005). Another longitudinal study found a one-time positive effect of children on productivity (a possible artifact of planning for a child). This was followed by a negative effect on productivity growth for both men and women academics who had a child, with a larger productivity penalty for mothers (Hunter and Leahey 2010). Men and women spend the same overall amount of time on their paid work each week, but faculty mothers of young children dedicate less time to research. Compared with men assistant professors, women assistant professors reported spending two fewer hours on research, one additional hour on teaching, one additional hour on mentoring and service, two and a half more hours on housework, and two more hours on care work each week (Misra et al. 2012).

These effects have only been exacerbated during the pandemic. During the pandemic, women faculty members are spending even less time on research, relative to men. U.S. and European principal investigators with young children reported a 17 percent larger reduction in research time during the pandemic compared with scientists without young dependents. This is separate from a 5 percent larger decline in research time reported by women scientists, all else equal (Myers et al. 2020). Women academics with children at home report spending an average of half an hour less per day than men with children and an hour less per day than their men colleagues without children on research during the pandemic, along with increases in childcare and housework (Deryugina et al. 2021). Of course, gender and parenthood status are not perfectly predictive of increased caregiving

demands during the pandemic.⁶ Some men academics are primary caregivers, and many women academics do not have children at home. But even when men and women academics both have young children, men’s careers are less likely to be adversely affected (Mason et al. 2013). Caregiving adversely affects women’s mental health more than it does men’s (Penning and Wu 2015). Even among parents who report splitting childcare labor evenly, the productivity cost is higher for women (Derrick et al. 2019). On the whole, this body of work points to a greater productivity penalty for mothers than fathers.

Dual-Career Academics. In a special case of the first explanation, women academics are more likely than men to be in relationships with other academics, giving them statistically less working time on average than men academics. In the natural sciences, 48 percent of women have academic partners compared with 35 percent of men (Schiebinger et al. 2008). Among these academic couples, 83 percent of women scientists but only 54 percent of men scientists are coupled to other scientists (Schiebinger et al. 2008). In dual-academic couples, women still do a far greater share of all household duties. However, academic women in couples with academic men have slightly more egalitarian sharing of household duties than academic women in other types of relationships (Schiebinger and Gilmartin 2010).

So what does this mean for the transition to working from home? Assume, for the sake of argument, that dual-career academics decide to share childcare exactly equally during the pandemic, while other couples continue a less even division of labor. This means that a greater fraction of women than men are doing 50 percent of the childcare labor, because 48 percent of women, but only 35 percent of men scientists, have academic partners. In our thought experiment, the remainder of men scientists (65 percent) do less than half of the childcare, while the remainder of women scientists (52 percent) do more than half the childcare. So on average, men scientists are doing far less than half the childcare while women are doing far more.⁷ Statistically, among all academics, women will be less productive. Add to this the fact that women in dual-academic couples are more likely to

⁶Children are not the only people who may need more care than usual during COVID-19. Women are generally responsible for the majority of caretaking work for elderly relatives (Varner and Drago 2000). However, time-tracking studies have found no difference in faculty time spent on elder care (Misra et al. 2012).

⁷This computes even if we base the calculation on only those scientists with stay-at-home partners: the remainder of men scientists (20 percent) would do less than half the childcare, with women with stay-at-home partners (only 5 percent) doing less than half the childcare. Note that these are not natural science-specific percentages for stay-at-home partners (Schiebinger et al. 2008).

place equal value on their and their partner's careers than are men in dual-academic couples (Schiebinger et al. 2008). Given this imbalance, women academics may find their time less protected than that of their partners'. Thus, even if women scientists increasingly insist on an even division of domestic and childcare duties in their homes, they will continue to do more than the average academic man.

Many academic men who are committed to gender equality strive to do their part by sharing domestic and childcare duties equally with their partners, but achieving gender equality in domestic labor and childcare across the entire population of academics would require either (1) all households to split duties evenly or (2) large numbers of men to do more than half of the domestic and childcare work in their households, to compensate for the large number of households in which men and women have traditional gender roles. Gender equality in academia cannot rely on the coordinated behavior of hundreds of thousands of households, so we point to institutional supports later on.

Service

A second potential mechanism that might explain the gender imbalance in preprint submissions is an increase in service expectations during the pandemic. In a survey of tenured and tenure-track faculty members from four-year colleges and universities, women reported about 30 more minutes per week of service than men, even after controlling for rank, race, and discipline. Full professors spent the most time, with women full professors reporting notably more time spent on service than men professors (Guarino and Borden 2017).

The advent of the pandemic also created needs for universities to develop both short- and long-term plans for academic and student life (The Chronicle of Higher Education 2020b). Most universities and colleges dealt with this administrative burden by developing working groups that included faculty members, another form of internal university service. As the gender gap in service time is driven primarily by internal service (Guarino and Borden 2017), this increased need likely exacerbated the demands on women faculty members' time during the COVID-19 pandemic.

The Transition to Online Teaching

The third potential mechanism that may explain the gender gap in productivity rates is that the pandemic may have exacerbated women's already greater teaching expectations. Research shows women generally have academic positions with higher teaching commitments (AAUP 2001; Misra et al. 2011). Women are less likely to hold positions at research universities and more likely to work in adjunct or other temporary teaching roles (Finkelstein, Conley, and Schuster 2016; Monks 2009; Steinþórsdóttir et al. 2018). Research suggests that online teaching takes more time, especially

when initially creating a class, than in-person teaching (Kenny and Fluck 2017; Myers et al. 2020; Tomei 2006). In the spring term at the beginning of the COVID-19 shelter-at-home orders, instructors were asked to quickly move their classes online (The Chronicle of Higher Education 2020a). This created greater time demands on faculty members with larger teaching responsibilities. As these faculty members are disproportionately women, the reduced research productivity of women during the shelter-at-home orders may be due in part to increased teaching demands. This proposed mechanism of increased teaching demands is supported by findings from a qualitative study of academic mothers during the early pandemic, who reported prioritizing teaching and mentoring, while discarding or postponing research (Minello, Martucci, and Manzo 2020).

Furthermore, women are generally expected to perform more emotional labor in the classroom than men (Bellas 1999). This involves more outreach to underperforming students and more time spent in office hours supporting students' personal and psychosocial development (El-Alayli, Hansen-Brown, and Ceynar 2018). Women faculty members, particularly women of color faculty members, must engage in a disproportionate amount of emotional labor for the university, especially for required diversity courses (Moore et al. 2010). With the dramatic changes to students' personal lives that came with the COVID-19 pandemic and associated shelter-at-home orders, women professors likely spent more time on emotional labor tasks.

Methods

Compiling the Data Set

We drew our data on preprints from two sources. The biological science preprint server bioRxiv is maintained by Cold Spring Harbor Laboratory. Run by Cornell University, arXiv is a preprint server mainly for physics, math, computer science, and statistics, but it also accepts preprints in electrical engineering and systems science, quantitative finance, economics, and quantitative biology. We scraped data using the contributed R packages arXiv (Karthik and Broman 2019) and rbiorexiv (Fraser 2020), which provide interfaces for the arXiv and bioRxiv application programming interfaces (APIs), respectively, in the R programming language.

We began by downloading all submission records for March 15 to April 15, 2020 (inclusive), during the COVID-19 pandemic. We chose this date range to roughly correspond to the period when the largest number of schools closed worldwide in attempts to slow the spread of COVID-19. On March 15, 2020, an estimated 485 million children were out of school because of the pandemic (28 percent of the world's schoolchildren), and this number quickly grew to 1,577 million children (90 percent of the world's schoolchildren) by April 15, 2020 (UNESCO Institute for Statistics 2020), before declining somewhat in late April as

certain countries or states reopened schools. For comparison, we also scraped submission data for the same dates the previous year (i.e., March 15 to April 15, 2019, inclusive), before the pandemic.

Next, we expanded the date range to scrape all the preprint submission data for January 1, 2020, to June 30, 2020 (inclusive), to monitor changes in the gender composition of preprint authorships immediately before widespread school and childcare closures, and during the pandemic, which was declared by the World Health Organization on March 11, 2020, and continues at the time of writing. On June 30, 2020, 1,067 million children were out of school (61 percent of the world's schoolchildren) (UNESCO Institute for Statistics 2020).

We completed two complementary analyses. The year-over-year analysis, comparing March and April 2020 with March and April 2019, evaluates the effect of the pandemic, holding constant time of year. This is important because paper submission rates can vary throughout the year, depending on holidays and the demands of the academic calendar. However, we also conducted a second analysis, in case March and April 2019 happened to be aberrant (i.e., in case there happened to be unusual productivity by men or women academics in March and April 2019). The analysis of January to June 2020 serves to evaluate the effect of the pandemic, holding constant longer term trends in preprint submissions that may complicate year-over-year analyses. The pandemic's effects have occurred against a backdrop of women's increasing participation in STEM. Thus, the short-term January to June 2020 analysis is especially important, because there may be few trends year over year if women's productivity increased relative to men's before the pandemic but declined during the pandemic (i.e., these forces may tend to cancel out).

We used each author's first name to predict gender (see below), but the bioRxiv API returned first names only for corresponding authors. One of us (M.E.F.) previously published an analysis that included only corresponding authors from bioRxiv (Frederickson 2020). To obtain first names for all authors of bioRxiv preprints, we first compiled submission data from the bioRxiv API, then used the `rcrossref` package in R (Chamberlain et al. 2020) to look up each digital object identifier and download the citation in BibTeX format, which included first and last names for all authors. This workaround allowed us to collect first names for all authors who provided them when they submitted preprints to bioRxiv.

For all analyses, we define the unit of interest as a unique author-paper, which we refer to as an authorship. Following other bibliometric analyses (e.g., King et al. 2017), we include authors who submitted multiple preprints, not only unique authors. Thus, an *authorship* is an author on a single paper.

Predicting Author Gender

After extracting the first names of authors, we assigned gender to author names using the R `gender` package (Mullen

2019). This package returns the probability that a name is that of a man or a woman by comparing the name with names in a database; we used the U.S. Social Security Administration baby names database. The R `gender` package matches names on the basis of a complete sample of Social Security card applications. As a result, prediction is less robust for scientists born outside the United States.

We did not attempt to predict the gender of names not matched to the U.S. Social Security Administration baby names database, because such efforts to increase coverage could come with a loss of accuracy. A study comparing approaches using name matching on the basis of Social Security records with others showed that including data sets from other countries, manual coding of names, or a unisex category might produce more biased results (Wais 2016). Among the approaches studied, there was a trade-off between predicting gender for as many individuals as possible and maximizing prediction accuracy.

Nonetheless, matching names to a names database is a brute-force method of predicting gender, and it has limitations (see Mullen 2019). By using this method, we are not assuming that individuals are correctly gendered in the resulting data set but merely that it provides insight into gender's effects in aggregate across the population of preprint authors. This approach clearly misgenders or excludes some individual authors, but it is necessarily used to measure gender bias in large data sets. Both the specific package we used and other similar gender algorithms (e.g., `genderize.io`) have been used in other studies (e.g., Amano-Patiño et al. 2020; Vincent-Lamarre, Sugimoto, and Larivière 2020b; West et al. 2013).

Summary Statistics and Modeling Approach

There were 149,124 preprints in the data set we assembled: 114,632 arXiv preprints and 34,492 bioRxiv preprints. These preprints had a total of 808,227 nonunique authorships: 549,512 arXiv authorships and 258,715 bioRxiv authorships. Some individuals authored more than one preprint in the data set.

For each preprint with multiple authors, we determined whether authors were listed in alphabetical order by last name. Importantly, some preprints will have authors listed in alphabetical order just by chance, no matter which authorship order convention they used (e.g., preprints with two authors should list them in alphabetical order 50 percent of the time by chance alone). We compared the observed proportion of preprints with authors in alphabetical order with the expected proportion if author order were determined at random (Figure A2). Thirty-four percent of arXiv preprints with multiple authors (33,034 of 98,050) listed authors in alphabetical order, compared with only 7 percent of bioRxiv preprints (2,372 of 33,684). The observed proportion of bioRxiv preprints with authors in alphabetical order was almost identical to the expected

proportion due to chance, but arXiv has an excess of preprints with authors in alphabetical order (Figure A2). These results confirm that bioRxiv preprints do not list authors in alphabetical order by convention, but arXiv preprints sometimes do, especially in math and economics and quantitative finance (Figure A1).

We inferred the gender of 266,133, or 48.4 percent, of arXiv authors and 195,204, or 75.5 percent, of bioRxiv authors, with the rest omitted from subsequent analyses. This lower success rate for predicting author gender for arXiv than bioRxiv preprints reflects the fact that arXiv preprints are more likely to list large consortia as authors (e.g., CMS Collaboration), have authors who provide only first initials, or have authors who have names not in the U.S. Social Security names database. Nonetheless, similar fractions of authorships with unknown gender are typical for large data sets (Wais 2016).

Using the data from January 1 to June 30, 2020, we modeled the number of preprint authorships per day as a function of submission date and gender.⁸ We included the interaction between submission date and gender in our linear models to determine whether the number of men authorships is increasing significantly faster through time than the number of women authorships (i.e., whether growth in the number of men authorships has a significantly higher slope than growth in the number of women authorships). We also included the day of the week as a main effect in all models to account for the fact that far fewer preprints are submitted on Saturdays and Sundays. We ran a separate model for each author position (i.e., first, middle, last, and sole) and data set (i.e., arXiv and bioRxiv). We square-root-transformed the number of preprint authorships per day to improve the normality of residuals and checked residual diagnostic plots for all models. We then used the *car* package (Fox and Weisberg 2019) in R to perform analyses of variance with type III sums of squares.

Results

We found that all analyses of both arXiv and bioRxiv preprints show a widening gender gap in last (or “senior”) authorships but more mixed results for other authorship positions. For arXiv, all authorship positions combined and most authorship positions analyzed separately also show a growing gender gap. In contrast, for bioRxiv, only last authorships show a much larger gender gap during than before the pandemic; analyses of other authorship positions and all authorships combined show few differences between genders. In fact, year over year, women actually gained substantial

ground relative to men as first authors of bioRxiv preprints. We also separately analyzed physics, math, and computer science preprints submitted to arXiv and found that all authorship positions combined showed an increasing gender gap in all three fields, except in the year-over-year analysis for computer science.

Year-over-Year Comparisons

arXiv Preprints from 2019 to 2020. We began by comparing arXiv preprint authorships between March 15 and April 15, 2020, during the start of the COVID-19 pandemic, with the same dates in 2019. We found that the number of arXiv preprint authorships increased between 2019 and 2020 for all authorship positions and genders (Figure 1). Increases in preprint submissions between 2019 and 2020 are perhaps not surprising, as scientific output and the popularity of preprint servers have both been increasing in recent years (Penfold and Polka 2020), and the time-sensitive nature of COVID-19 research may also have encouraged greater use of preprint servers among scientists (Fraser et al. 2020). On the other hand, we might have expected decreased productivity overall during the pandemic because of illness and bereavement and also laboratory closures affecting experimental scientists. Nonetheless, there were 14,978 submissions to arXiv between March 15 and April 15, 2020, compared with 13,733 submissions in the same date range in 2019, an increase of 9.1 percent.

Although arXiv preprint submissions were up overall, men authorships grew more year over year than women authorships, both for all authorship positions combined and for all authorship positions analyzed separately, except first authorships (Figure 1). For all authorship positions combined, men added 1,648 authorships and women added 189 authorships in March and April 2020 compared with March and April 2019, corresponding to increases of 6.4 percent and 2.7 percent for men and women, respectively. Put differently, in March and April 2019, 78.7 percent of arXiv authorships were men, but 89.7 percent of the additional authorships in 2020 were men.

Next, we separately analyzed the data for preprints with single authors and for first, middle, and last authorships of multiauthored preprints. There were 112 more preprints sole-authored by men but just 7 more preprints sole-authored by women in March and April 2020 than in March and April 2019, representing increases of 9.6 percent and 3.7 percent, respectively (Figure 1). In contrast, there were 514 more men first authorships and 145 more women first authorships in March and April 2020 than in March and April 2019, or 9.2 percent and 9.8 percent increases, respectively. In other words, in absolute terms, there was a greater increase in men than women first authorships of multiauthored arXiv preprints between March and April 2019 and March and April 2020, but women made slightly greater gains than men in the first author position when measured as a percentage change, year over year.

⁸Note that although many more preprints are submitted to arXiv than bioRxiv every day, because we treated the number of preprint authorships per day as the unit of analysis in our statistical models, all models had the same degrees of freedom and thus similar statistical power to detect gender differences.

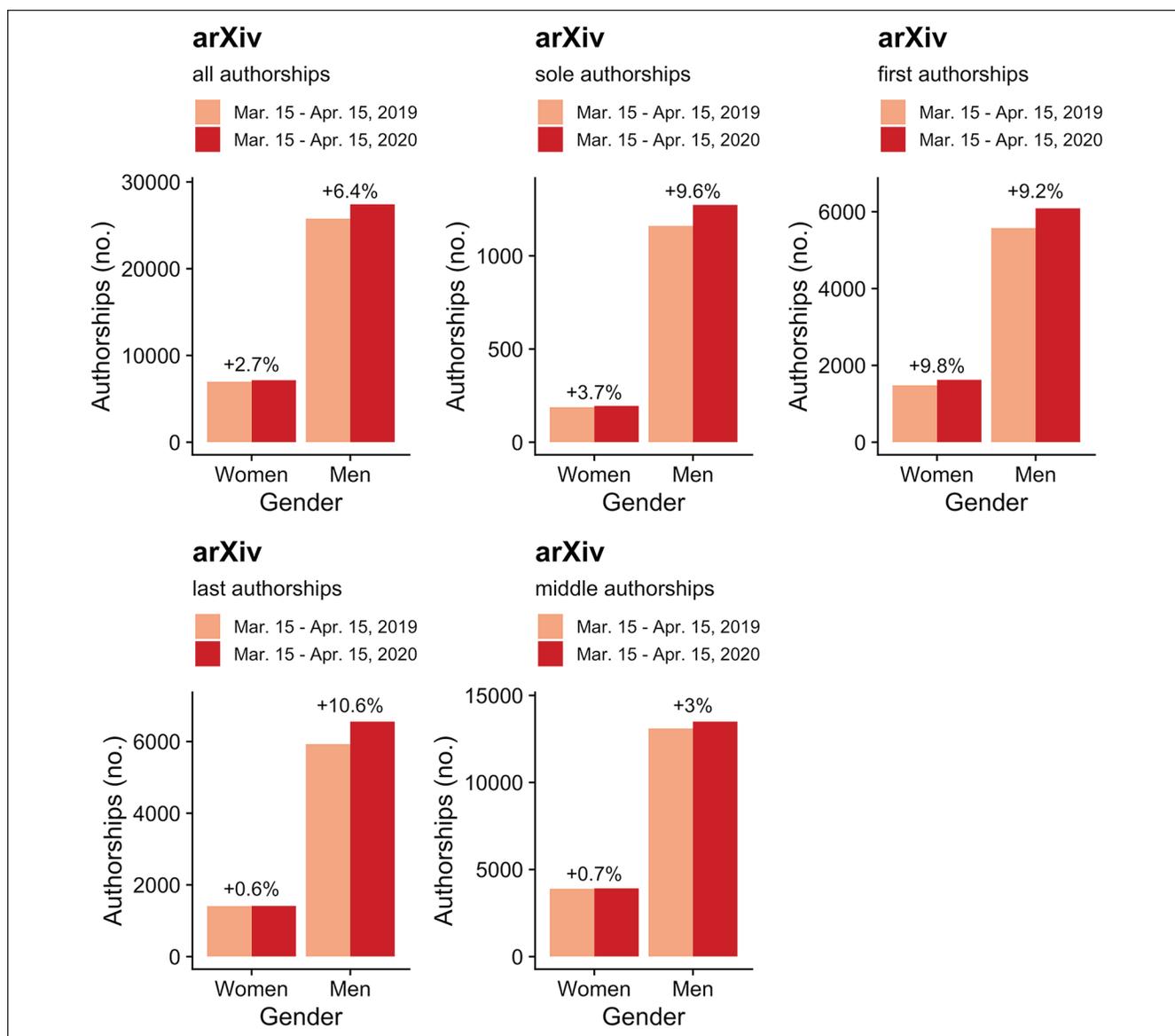


Figure 1. Women versus men authorships of arXiv preprints from March 15 to April 15, 2020, and March 15 to April 15, 2019. First, middle, and last authorships are for multiauthored preprints only. Percentages above bars show percentage change year over year for each author position and gender.

However, women lagged behind men in gains as middle and last authors of multiauthored papers. Specifically, there were 627 more men last authorships but only 8 more women last authorships between March and April 2019 and March and April 2020. This represents a 10.6 percent increase in men last authorships, while women last authorships were essentially unchanged over the same period, having grown just 0.6 percent. Finally, the number of women middle authorships rose by 29 from March and April 2019 to March and April 2020, a change of just 0.7 percent, while the number of men middle authorships rose by 395, or 3 percent. In summary, except for first authorships, men made greater gains than women as arXiv preprint authors during the

pandemic, compared to the same dates the previous year. Furthermore, the gender gap is growing fastest among last authors.

Unlike bioRxiv, which holds preprints for the biosciences, the arXiv repository serves many academic fields. To understand how the pandemic is affecting gender disparities in different fields, we compared the fields with the largest numbers of preprints (physics, computer science, and mathematics; see Figure A1) across years. In the year-over-year analysis, the general pattern of less rapid growth in the number of women than men authorships holds in physics and math, but not computer science, where the growth in women authorships outpaced that of men authorships in relative (but not

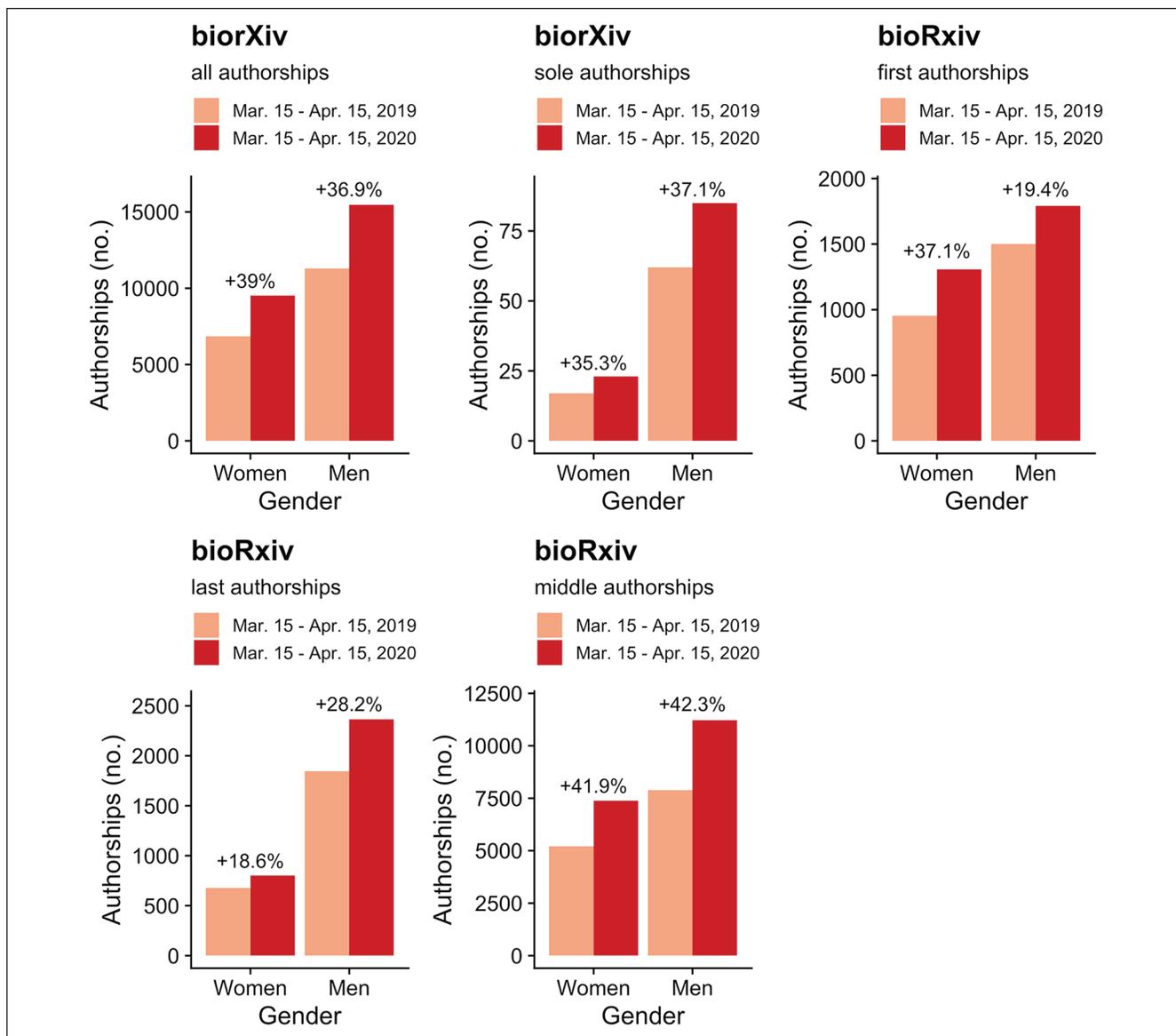


Figure 2. Women versus men authorships of bioRxiv preprints from March 15 to April 15, 2020, and March 15 to April 15, 2019. First, middle, and last authorships are for multiauthored preprints only. Percentages above bars show percentage change year over year for each author position and gender.

absolute) terms (Figure A3). We cannot know whether the growth in women authorships in computer science is less than it would have otherwise been if the pandemic had not happened, as perhaps women were already gaining ground.

bioRxiv Preprints from 2019 to 2020. We conducted an identical analysis for preprints in the biological and life sciences by analyzing submission data from the preprint repository bioRxiv. In general, we found that the pandemic has not exacerbated gender differences among bioRxiv preprint authors as much as among arXiv preprint authors, although there has still been a growing gender gap in the last author position.

As a preprint repository, bioRxiv receives fewer submissions than arXiv, but the number of bioRxiv submissions grew from 3,381 preprints between March 15 and April 15, 2019, to 4,437 preprints over the same dates in 2020, an increase of 31 percent. Across all author positions, women authorships have actually increased a little more than men authorships year over year, as a percentage change. In absolute terms, there were 2,669 more women authorships compared with 4,168 more men authorships in March and April 2020 than in March and April 2020, representing increases of 39 percent and 36.9 percent, respectively (Figure 2). This is consistent with a long-standing trend in which women had been narrowing the gender gap in the biological and life

sciences before the pandemic, although we note that our analysis does not allow us to determine whether women would have made even larger gains in preprint authorships if not for COVID-19.

Next we again broke this down by author position and discovered that this pattern was driven by a large increase in the number of women first authorships on multiauthored preprints. Both as a percentage change and an absolute change year over year, there was a larger increase in the number of women first authorships than the number of men first authorships. There were an additional 354 women first authorships (37.1 percent) and 291 men first authorships (19.4 percent) in March and April 2020 compared with the same dates in 2019.

In contrast, sole, middle, and last authorships all increased faster for men than women, although there is a large gender difference only for the last author position. Women submitted 6 additional sole-authored preprints to bioRxiv (up 35.3 percent) in March and April 2020 compared with March/April 2019, while men submitted 23 more sole-authored preprints (up 37.1 percent); however, the absolute numbers are small, limiting the conclusions we can draw from these data. There was slightly more growth among men than women middle authorships, with an additional 2,183 women middle authorships and 3,334 men middle authorships between March and April 2019 and 2020, representing percentage gains of 41.9 percent and 42.3 percent, respectively. But although women almost kept pace with men as middle authors, they lagged far behind men as last authors; there were 520 more men last authorships but only 126 more women last authorships between March and April 2019 and 2020, increases of 28.2 percent and 18.6 percent, respectively (Figure 2).

Thus, compared with arXiv, the pattern among author positions in year-over-year change is more mixed: sole, middle, and last men authorships increased at a faster rate than women authorships, but with a pronounced difference only for last authorships, while women in first author positions continued to increase their rate of productivity, potentially reflecting prepandemic trends toward greater gender equity. These findings, however, are complicated by our analyses of the first six months of 2020 in the next section.

Trends in Preprint Submissions Immediately before and during the COVID-19 Pandemic

Next, we looked back over the months leading up to widespread stay-at-home orders and school and childcare closures in late March or early April 2020. These measures were implemented to different degrees and on different dates in different parts of the world, but we assumed that their effects would be most pronounced (globally) starting in March 2020. We also expanded our analysis forward in time through June 30, 2020. Thus, we analyzed data for the first six months of 2020.

arXiv Preprints in the Early Pandemic. For the arXiv data set, the pattern of women making smaller authorship gains during the pandemic than men holds across all authorship positions, but with varying effect sizes (Figure 3, Table 1). Again, during the pandemic, the number of men authorships has grown faster than the number of women authorships, visible in Figure 3 (and Figure A4) as the divergence of the two lines. We tested for differences in the slopes of these lines in linear models, by predicting the number of preprint authorships per day as a function of gender, date, day of the week, and a gender \times date interaction effect. Gender always had a significant main effect, which means that there were always significantly more men authorships than women authorships at the model intercept (i.e., on January 1, 2020) (Table 1). Day of the week also always had a significant effect on the number of preprint authorships, with significantly fewer submissions on weekends, and generally more on Mondays and Tuesdays than later in the workweek (Table 1). Because women were the reference group in our linear models, the main effect of date tests whether women authorships increased through time, from January 1 to June 30, 2020.

For everything except sole authorships, the number of women authorships increased significantly over this period (Table 1). For sole authorships, there was no significant main effect of date, meaning that the number of arXiv preprints sole-authored by women stayed flat between January 1 and June 30, 2020 (Table 1, Figure 3). The gender \times date interaction term in the linear models tests whether men and women authorships increased at the same rate through time; again because women are the reference group in our models, positive interaction coefficients mean that men have outpaced women in the growth of authorships, while negative interaction coefficients would mean that women have outpaced men. The magnitude of the (positive) gender \times date coefficients specifies how much faster men authorships grew over the first six months of 2020 than women authorships. For all five authorship categories (all authorships combined, sole authorships, and first, last, and middle authorships on multiauthored preprints), there was a significantly positive gender \times date interaction term (Table 1). In other words, the rate of increase in men authorships was always steeper than the rate of increase in women authorships. For all arXiv author positions, the number of men authorships has grown faster than the number of women authorships during the pandemic.

We also split this analysis by field for the arXiv repository, and the general pattern holds in physics, mathematics, and computer science (Figure A4, Table A1). The date \times gender interaction term is significant, meaning the figures show a steeper increase in men than women authorships between January 1 and June 30, 2020. The magnitude of the interaction (the slope of the line) is greater for physics and computer science and smallest (but still significant) for math (Table A1). The figure for computer science also shows that the number of men authorships is lower in late March and early

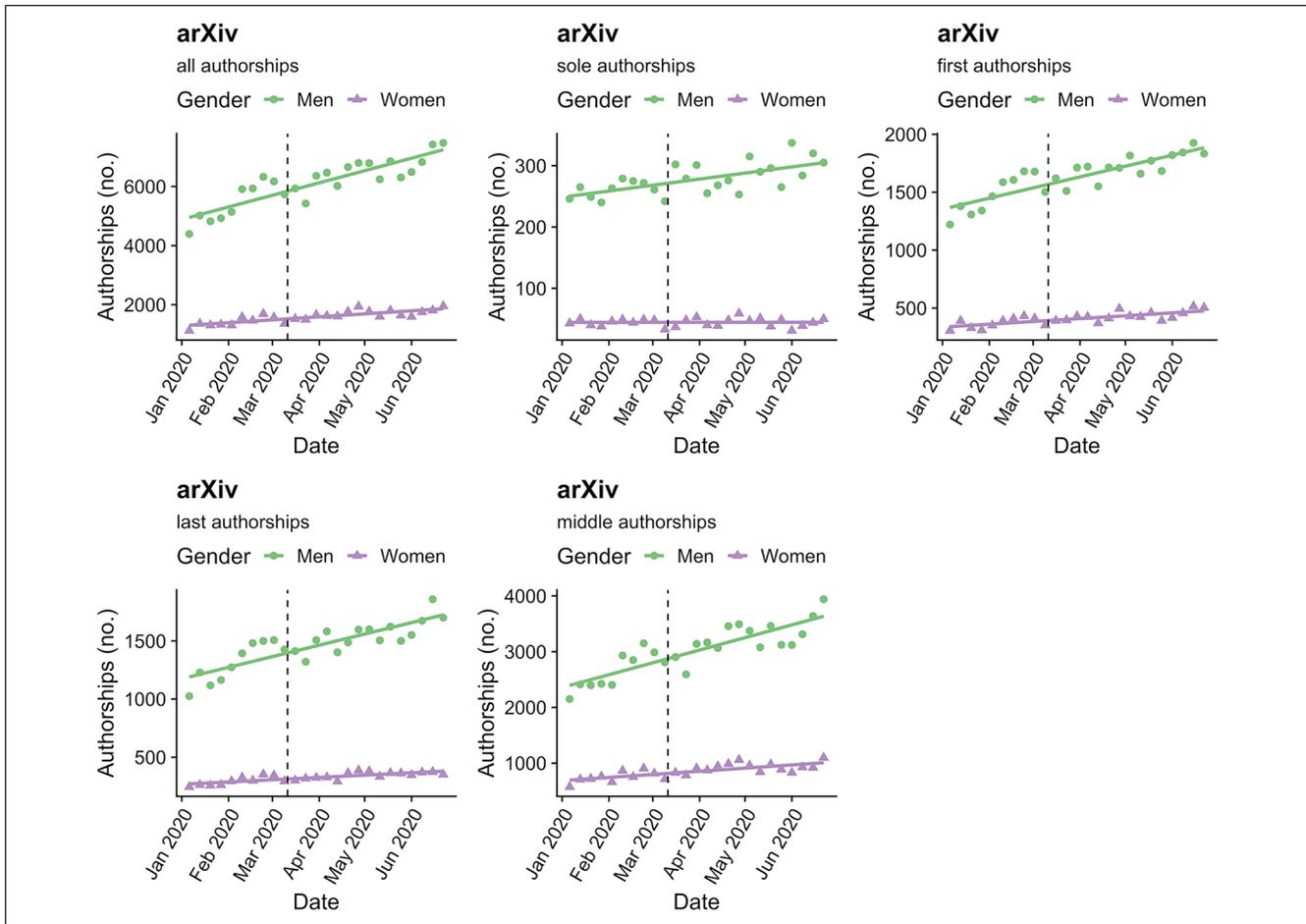


Figure 3. Women (purple triangles) versus men (green circles) authorships of arXiv preprints in the first half of 2020. Each dot is the sum of authorships for one week. First, middle, and last authorships are for multi-authored preprints only. The dashed vertical line is March 11, 2020, the day the World Health Organization declared COVID-19 a pandemic. Solid lines are simple linear regressions for visualization purposes; see Table 1 for results of statistical models.

Table 1. Table of Coefficients Estimated by Linear Models for arXiv Preprint Authorships per Day.

	All	Sole	First	Last	Middle
Intercept	7.322***	1.678***	3.973***	3.371***	5.080***
Gender	12.491***	3.434***	6.763***	6.585***	8.242***
Date	.016***	.001	.008***	.007***	.012***
Monday	9.201***	1.377***	4.446***	4.138***	6.969***
Tuesday	9.221***	1.113***	4.317***	4.097***	7.110***
Wednesday	8.101***	1.071***	3.897***	3.677***	6.128***
Thursday	8.399***	1.134***	3.970***	3.794***	6.415***
Friday	6.915***	.622***	3.221***	3.075***	5.357***
Saturday	-.777	-.471***	-.549*	-.355	-.441
Gender × date	.018***	.003**	.008***	.009***	.013***

Note: Coefficients are not back-transformed from the square-root scale. Reference groups are women and Sunday. A positive gender × date coefficient means that men authorships are growing faster than women authorships.

* $p < .05$. ** $p < .01$. *** $p < .001$.

April 2020, compared with right before and right after, perhaps explaining why women gained on men year over year in

this date range (i.e., late March and early April 2020 appears aberrant in computer science, but not in physics and math).

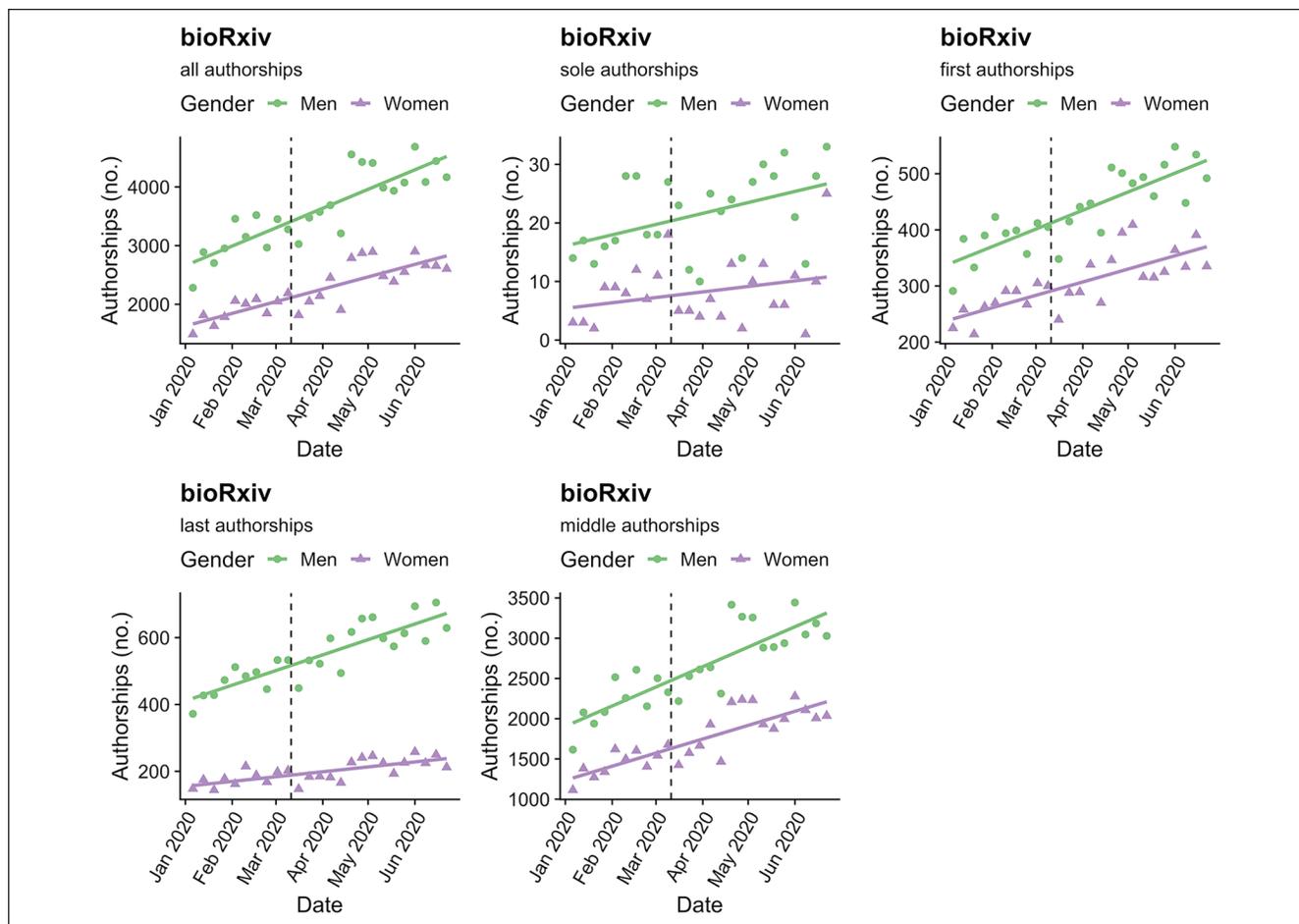


Figure 4. Women (purple triangles) versus men (green circles) authorships of bioRxiv preprints in the first half of 2020. Each dot is the sum of authorships for one week. First, middle, and last authorships are for multi-authored preprints only. The dashed vertical line is March 11, 2020, the day the World Health Organization declared COVID-19 a pandemic. Solid lines are simple linear regressions for visualization purposes; see Table 2 for results of statistical models.

Table 2. Table of Coefficients Estimated by Linear Models for bioRxiv Preprints per Day.

	All	Sole	First	Last	Middle
Intercept	9.678***	.472**	3.687***	2.691***	8.510***
Gender	4.072***	.806***	1.125***	2.833***	3.087***
Date	.033***	.001	.011***	.008***	.030***
Monday	3.599***	.104	1.362***	1.306***	3.071***
Tuesday	6.111***	.295	2.316***	2.271***	5.175***
Wednesday	6.077***	.256	2.215***	2.151***	5.229***
Thursday	7.660***	.276	2.857***	2.784***	6.549***
Friday	6.753***	.068	2.490***	2.489***	5.782***
Saturday	2.440**	.053	.865**	.854**	2.125**
Gender × date	.007	.001	.001	.006*	.005

Note: Coefficients are not back-transformed from the square-root scale. Reference groups are women and Sunday. A positive gender × date coefficient means that men authorships are growing faster than women authorships.

* $p < .05$. ** $p < .01$. *** $p < .001$.

bioRxiv Preprints in the Early Pandemic. As with arXiv submissions, we also compared bioRxiv submissions across the first six months of 2020 to investigate the effect of the onset of the pandemic on submissions by authorships in each position

(Figure 4). The number of submissions is rising across the first six months for both genders, significantly so for all author positions except sole authorships (Table 2). However, there are no significant gender × date interaction effects for all

authorship positions in aggregate, sole authorships, first authorships, or middle authorships (Table 2). This implies that the changes in the publication rates for men and women are statistically indistinguishable at all author positions, except last authorships. Furthermore, although the number of women first authorships on bioRxiv preprints grew more year over year than the number of men first authorships (Figure 2), the data and linear model results for the first six months of 2020 suggest women have kept pace with (but not outpaced) men as first authors during this period (Table 2, Figure 4). This implies that the year over year differences may reflect relative growth in women first authorships that happened late in 2019. The relative rates of men and women first authorships have held steady during the pandemic.

Nonetheless, for bioRxiv preprints as for arXiv preprints, the number of men last authorships has grown significantly faster than the number of women last authorships during the first six months of 2020. There is a significant gender \times date interaction term (Table 2), with men increasing in productivity faster than women for last author positions in bioRxiv from January to June 2020. This interaction effect is visible in Figure 4 as the divergence of the two lines in the last authorships panel.

Discussion

Women scientists have experienced a productivity penalty from the social and structural changes accompanying the COVID-19 pandemic, but not in all authorship positions. We found identical patterns in arXiv and bioRxiv for the increasing gender gap in the last author position: women's relative rate of productivity in last authorships has declined significantly. In the arXiv repository—which covers the fields of physics, math, statistics, economics and quantitative finance, electrical engineering and systems science, computer science, and quantitative biology—there was also a significant reduction in women authorships in the first, middle, last, and sole author positions. We found no such effect in the bioRxiv repository, which publishes preprints from the biological sciences. The difference between the repositories is not a problem of statistical power. Instead, we suggest that these findings are consistent with the fact that a greater proportion of authorships in the arXiv preprint repository are with authors in alphabetical order, whereas author order in the biological sciences is almost universally decided by contributions to the paper (see Figure A2; Waltman 2012), and senior women may have experienced greater constraints on productivity during the pandemic.

Notably, first authorships by women increased significantly more than men between 2019 and 2020 in bioRxiv and slightly more as a percent change year-over-year in arXiv, likely a result of the increasing representation of

women in science (Fox et al. 2017). However, in the arXiv repository, we still saw a relative decline (compared with men) in first authorships among women in the early months of COVID-19, reflecting a slowdown in women's productivity in the physical sciences and mathematics. Given the large representation gap that yet remains in these fields, any deceleration in productivity will reduce gender equity. Although the first authorship gender gap in bioRxiv actually shrunk between 2019 and 2020 and was unaffected in early 2020, we find that the rate of submission of bioRxiv preprints by women in last authorships has been negatively affected by the pandemic, as it has in the arXiv data set.

Our results are consistent with an extensive literature on gender-based productivity differences. This includes the facts that women academics are disproportionately responsible for childcare and household work, more likely to be in dual-career relationships with other academics, and have more service and teaching responsibilities. The true cause is likely some combination of these. The extraordinary childcare burden brought on by the COVID-19 pandemic, disproportionately shouldered by women, is consistent with our finding that gender gaps are growing fastest among last authors. Women academics are more likely to reduce their work hours and deprioritize their careers when family needs arise. Our society has long depended on invisible and undervalued care and domestic work (England, Budig, and Folbre 2002; Madowitz, Rowell, and Hamm 2016); the pandemic has undermined these structures that support the “ideal worker.” Faced with added domestic responsibilities, together with disproportionate service, teaching, and emotional labor, senior women faculty's research productivity has decreased during the pandemic.

However, in the first, middle, and sole author positions, women authorship rates have not been affected by the pandemic in bioRxiv—only in arXiv. This finding reveals that the underrepresentation of women scientists in the prestige authorship positions necessary for retention and promotion (in the biological sciences) and all authorship positions (in the physical sciences and mathematics) is only getting more inequitable during the COVID-19 pandemic. Publication productivity has important implications for cumulative advantage and visibility in careers (Fowler and Aksnes 2007; Leahey 2007). In a “publish or perish” world, the social fallout of the pandemic could set back the hard-won progress of women in STEM.

Although the overall conclusions have different emphases, our results align with other similar analyses of preprint repositories (Cui et al. 2020; Matthews 2020; Muric et al. 2020; Shurchkov et al. 2020), as discussed in the introduction. For example, we know that the gender gap in research focusing on COVID-19 is even larger than the general gender gap in

productivity during the pandemic (Amano-Patiño et al. 2020; Andersen et al. 2020; Gabster et al. 2020; Pinho-Gomes et al. 2020), suggesting that the disparity may be due primarily to women not joining new pandemic-related projects. Then again, we also see a growing gender gap among physics preprints in the arXiv repository, although fewer than 1 percent of physics preprints mention COVID-19, SARS-CoV-2, or coronavirus in the abstract.

Our results differ from those of published studies in two ways. First, Vincent-Lamarre et al. (2020a) found that the proportion of first authorships by women in bioRxiv and arXiv remained steady. One possible reason we find a small (but significant) increase in the gender gap among first authorships of arXiv preprints is that the gender prediction algorithm used by Vincent-Lamarre et al. (2020b) assigned gender to a greater proportion of names.⁹ We speculate that our results may reflect the predominance of North American and European names in our final data set (because we predicted gender using a U.S. names database), while perhaps Vincent-Lamarre et al. (2020a) included a more globally representative set of author names. The differences in how Europe and North America have responded to the pandemic, compared with other regions of the world, may therefore explain our conflicting results. Our findings may thus be limited to the context of North American and European academic science.

Second, a survey of pandemic time use found that those in the laboratory-based “bench” sciences experienced the most dramatic declines in time spent on research (Myers et al. 2020). Given this, we might have expected the reverse of our findings, as bioRxiv may have more submissions from those in the bench sciences than does the arXiv repository. Instead, differences in how the pandemic is affecting men’s and women’s preprint submissions to arXiv versus bioRxiv may reflect the different legacies of historical gender bias in the physical and life sciences, or different field-specific conventions or cultures regarding coauthorships and author order.

The trends we find in both bioRxiv and arXiv preprints support our hypothesis that the pandemic is disproportionately reducing the productivity of women scholars. How long this effect will persist, and what its downstream consequences might be for journal publications and academic careers, are open questions that can only be answered with time and further research. Our analysis could also be

extended to further examine the effects of field, institution, or country. Further research could investigate why fields differ in the consistency of women’s first authorship productivity during the early months of COVID-19, as these disciplinary differences might provide further insight into ways to support women scholars.

Policy Recommendations

Institutions of higher education need to heed these warning signals and take action now to prevent significant backsliding on gender equity. Given the novel nature of the challenges facing women during the pandemic, universities can and should do more than continue to implement known recommendations for supporting women faculty (Hill et al. 2010). As the growing gap in preprint submissions holds across the last author position, rather than making recommendations for each field, we suggest that universities take steps to support women principal investigators in general. Hiring, tenure, and promotion committees should recalibrate expectations and make them clear (Malisch et al. 2020). Bias creeps in when there is ambiguity (Ridgeway 2011). Because women increasingly choose occupations that allow them to reconcile the competing time demands of work and family (Damelang and Ebensperger 2020), it is crucial that universities provide institutional support for the unique challenges of this moment. In this section of the article, we outline research-based solutions institutions can implement to address the pandemic’s unequal impacts going forward.

Hiring and Evaluating

Universities should make a strong effort to communicate to departments and hiring committees the importance of producing diverse slates of job candidates and considering in their selection process the fact that the pandemic has negatively affected women and other underrepresented groups. We analyzed the pandemic’s effects on scholarly productivity only by gender, but we encourage similar efforts to explore how the pandemic is affecting Black, Asian, Latinx, and Indigenous scholars, as well as academics with disabilities and other equity-seeking groups. The pandemic has likely exacerbated other preexisting inequities because of the unequal disease burden (Williamson et al. 2020), discrimination and bias during the pandemic, and increased emotional labor.

Institutions can reduce bias by ensuring evaluations are holistic and transforming the process with equity in mind (Liera 2020). Acknowledging that gender bias exists in the pandemic is crucial to minimizing its impact; evaluators who think that bias is not happening in their fields are the key drivers of it (Begeny et al. 2020). Candidates should be given the opportunity to provide a written narrative, along with multiple forms of evidence (Htun 2020). However, asking academics to self-report how they have been individually affected could open the door to bias, whereby women are

⁹Vincent-Lamarre et al. (2020b) assigned gender to 79 percent compared with our 48 percent of names in arXiv and 92 percent compared with our 76 percent for bioRxiv. In addition to the U.S. Social Security names database, their gender disambiguation algorithm includes data from several other countries, including France, Canada, Korea, Lithuania, Iran, Romania, Brazil and Portugal, Serbia, Ukraine, Thailand, India, and Japan. A list from Wikipedia is also included, which includes names associated with more than 60 countries (Larivière et al. 2013).

generally penalized in evaluations for having children or spouses when men are not (Benard and Correll 2010; Correll, Benard, and Paik 2007; Rivera 2017).¹⁰ Institutions should explicitly not require any teaching evaluations from the transition period of the pandemic as part of hiring, retention, or promotion materials (Gonzales and Griffin 2020).

Universities will need to take action to ensure that women scholars are not disproportionately harmed in the tenure and promotion process. Many colleges and universities have been offering (sometimes automatic) extensions of the tenure clock. However, because this extension is offered to all assistant professors, it is not clear if it will address disproportionate harm to women. Tenure clock extension policies must be implemented carefully so as not to harm women scholars (Antecol, Bedard, and Stearns 2018; Manchester, Leslie, and Kramer 2013; Williams and Lee 2016). Furthermore, extensions delay the increase in pay and power that come with promotion for both women and men (Manchester et al. 2013). Tenure clock extensions are “not a panacea” (Malisch et al. 2020). If offered, “opt-out” extensions are preferable because the effort to opt out falls on the most privileged (Gonzales and Griffin 2020). When promoted, salary increases should be retroactive to when the faculty member would have initially gone up for tenure in the absence of the extension (Settles and Linderman 2020).

Committees must resist comparing productivity from the time of the extension, and they should specify to external reviewers the years for which candidates should be evaluated (Gonzales and Griffin 2020). Asking committees to completely discount papers written during the pandemic period is unrealistic. Institutional shared governance groups need to clarify expectations for productivity with gender equity in mind. Malisch et al. (2020) outlined recommendations for developing metrics and ensuring their institutional adoption; they also provided a set of questions as a starting point for evaluation committees.¹¹

Rethinking Productivity

Productivity can take different forms in a period in which rapid science is in high demand. Tenure and promotion standards could be updated with a statement to allow op-eds, reports, blogs, and other pieces written for popular audiences to be considered equally valuable to peer-reviewed papers during this time (Ellingson and Quinlan 2012); if not equally valuable, then some certain number of pieces could be considered equivalent to a peer-reviewed contribution. Researchers can also be encouraged to explore other types of

work like review articles, syntheses or commentaries, and data mining. Faculty development offices could encourage interdisciplinary collaborations among campus faculty. Small stipends, or even merely coordinating infrastructure, could be provided to encourage subject matter experts to collaborate with methodologists across fields. Such flexible approaches to thinking about productivity will make room for gender differences in methodology across disciplines during a time when some may be more difficult to use than others. It will also provide a structure for women researchers to deploy their existing expertise in productive new ways.

Institutions can also support their women faculty in sharing their expertise in other ways during this critical time. Women currently make up fewer than one quarter of COVID-19 experts in the media and national task forces. University press offices can also “amplify the voices of women with established records in infectious disease, pandemic response, global health, and health security” (Gabster et al. 2020:1969). This can be done by promoting existing research and helping facilitate the ongoing involvement of women scholars in COVID-19 policy making.

Getting Scientists Back to Work

Taking time out of the labor force for childcare has immense professional and economic costs for women—and men (Madowitz et al. 2016). Universities that expect professors to return to work need to be sure that their employees have access to adequate, safe childcare. Institutions should invest in high-quality, on-campus childcare (with appropriate safety measures) and offer small-group childcare not only for infants and preschoolers but for school-aged children in areas where schools continue to be closed (Fulweiler et al. 2021). Universities should also prioritize mothers for returning to offices and labs; space can be an issue for those in small homes, especially if children are being cared for at home.

Supporting Teaching

Rather than attempting to evaluate online learning or teaching efficacy using student evaluations, faculty members should be asked to document the move to online teaching using reflections or “before” and “after” syllabi (Gonzales and Griffin 2020). Students consistently rate women instructors lower on evaluations (Boring 2017; Laube et al. 2007; MacNeill et al. 2015). If student evaluations are used during online teaching, they should discount comments about organization, timeliness of responses, and interruptions and appearance during online class time, as these may be particularly affected by gendered dynamics during the pandemic.

Faculty members can also be invited to document the emotional labor and support provided to students during this time (Gonzales and Griffin 2020). Moving forward, administrators can support faculty members by providing templates for how to support students with common challenges.

¹⁰Although it is worth noting that among highly paid women, the motherhood penalty is explained largely by time out of the workforce (Budig and Hodges 2010).

¹¹The handout is available at <https://www.pnas.org/content/pnas/suppl/2020/06/17/2010636117.DCSupplemental/pnas.2010636117.sapp.pdf>.

To account for the greater teaching demands of moving courses online, institutions should consider shifting their percentage balances (for the relative importance of research, teaching, and service) for faculty evaluation for the duration of the pandemic. Universities could also consider providing more course releases during this time, even though budgets are tight (Settles and Linderman 2020). This could be administered through a special application-based program, giving early-career mothers (and especially single parents) priority. However, other potential consequences of such a program should be considered, including the growth of the adjunct workforce. An alternative could be providing additional teaching assistant support, with a very minimal application process to reduce barriers to its use.

Making Service and Funding Equitable

Even if course releases are not a possibility, institutions can implement structured interventions to ensure equity in service and teaching within departments. Ensuring that clear criteria are regularly applied even at the departmental level throughout these uncertain times will facilitate greater equity for women and underrepresented minorities (O'Meara et al. 2018).

Institutions that have diverted university grants should prioritize the return of funding for early-career mothers. Universities could provide flexible spending accounts so that mothers can hire caretakers for their children or elderly parents. Flexible spending accounts could also allow spending for housework for all faculty members, a benefit that is inclusive and also gender equitable (Schiebinger and Gilmartin 2010). Additional funds for home office items can reduce the challenges of working from home with children or other family members. Grant-funding institutions should provide extended deadlines and factor identity into research evaluation (Witteman, Haverfield, and Tannenbaum 2021).

Closing the Gender Pay Gap

At many institutions, women faculty continue to be paid lower salaries than men faculty, even after controlling for field and career stage (AAUP 2018; Fox et al. 2017). If universities took greater steps to close the gender pay gap, then women faculty in dual-career couples would not be the lower earning partners. Although research suggests that earning as much or more than their partners may not result in a more equitable division of labor at home (Brines 1994; Pew Research Center 2013; Tichenor 2005), increased wages for women scientists can be put to other uses, such as childcare. Realistically, it might already be too late for universities to significantly narrow the gender pay gap during the COVID-19 pandemic. But longer term investments in gender equality are still needed to ensure an equitable recovery after the pandemic and to guard against future exogenous shocks to academic productivity, be they to particular individuals or more widespread, as with COVID-19.

Structured Support

These kinds of changes will necessitate a focus on faculty development, shared governance, and flexible thinking about criteria for promotion and tenure. True gender equity in the academy also demands greater inclusion of non-tenure-track faculty members in developing strategic plans and initiatives to support faculty (Rosen and Lester 2020).

Many of these suggestions will cost money. However, compared with the substantial investments institutions have previously dedicated to recruiting and retaining qualified women faculty (Williams and Norton 2008), it would be penny wise and pound foolish to ignore the needs of this population during this critical time. An inclusive, diverse committee to oversee institutional programs and evaluation guidelines should be implemented at each college and university.¹² The service contributions to such a committee should be documented and valued for retention, tenure, and promotion (Malisch et al. 2020).

Although we know much about what helps support women and other underrepresented minority faculty members during regular circumstances, it remains to be seen if these recommendations will carry over to the pandemic academy. As universities implement programs to support women and minority faculty members, we need research on their efficacy so that future events do not lead to such consequential gender disparities.

For those who might read these suggestions and feel they do not go far enough, given the constraints of the modern neoliberal model of the university (Ferree and Zippel 2015), we argue for a “small wins” approach to organizational change (Correll 2017). Using research-based tools to reduce gender inequality, adapting these for the local organizational context, applying the intervention, and evaluating what enabled success will motivate organizational leaders to continue making change. Transformational gender equity is possible in the academy—one small change at a time.

Appendix

As the arXiv repository holds preprints for several academic fields, we sought to validate whether the patterns in authorship order in these fields within the repository match previous categorizations of publications (Waltman 2012).

Figure A1a displays the total number of preprints in the arXiv data set in each field. The arXiv data set is numerically dominated by physics, math, and computer science preprints. The other fields are only minor components.

¹²Suggestions for the operation and recommended actions of such a committee are available at <https://academicequity.smcm.edu/home/recommended-gender-equity-solutions#h.4p6zb1addy7h> (Malisch et al. 2020).

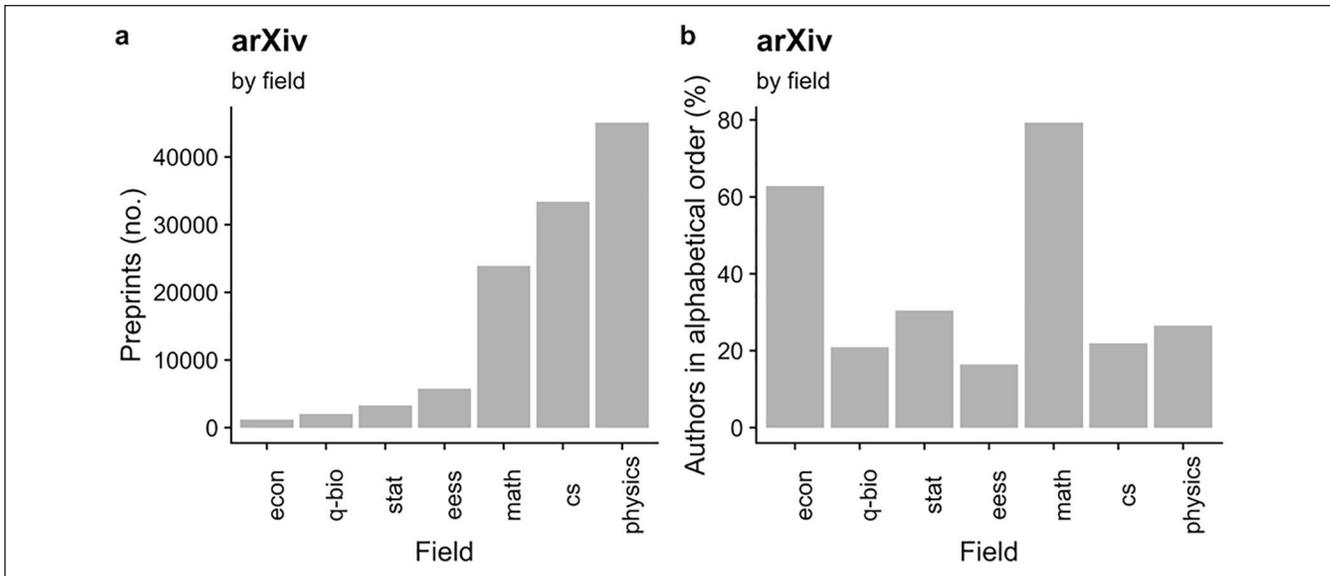


Figure A1. Number of preprints (a) and percentage of preprints in alphabetical order (b) by field within arXiv. The field represents the category used by arXiv, with the exception of “econ,” which groups economics and quantitative finance together, because each field has only a few preprints. cs = computer science; eess = electrical engineering and systems science; q-bio = quantitative biology.

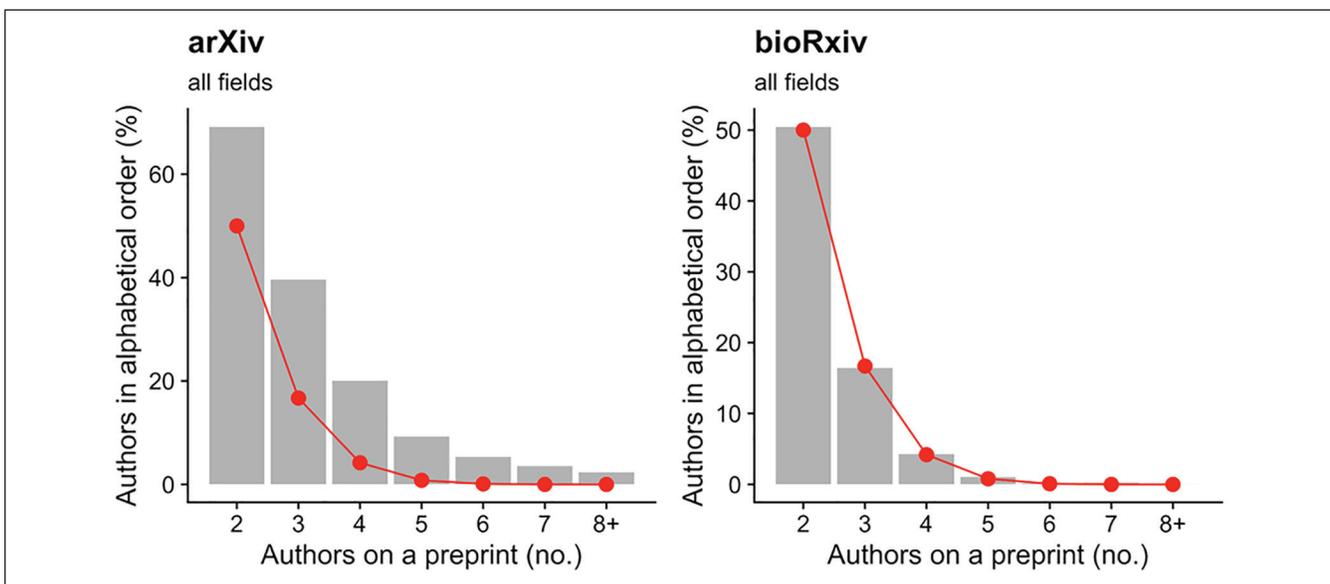


Figure A2. Percentage of authors in alphabetical order by number of authors on a preprint for arXiv and bioRxiv. Red lines and dots are what percentage should be in alphabetical order just by chance (no matter what authorship convention the authors used), and gray bars are what percentage are actually in alphabetical order.

Figure A1b shows the percentage of arXiv preprints in alphabetical order by field. The field is the category that arXiv uses (https://arxiv.org/category_taxonomy), except that we combined economics and quantitative finance because they each had a small number of preprints. Math and economics and quantitative finance are the fields with many preprints with authors listed alphabetically.

Figure A2 shows what percentage of arXiv and bioRxiv preprints have authors listed in alphabetical order, given the number

of authors on each preprint. We calculated the expected proportion of authors in alphabetical order by chance alone as $1/n!$, where n is the number of authors on a paper. For bioRxiv, the observed and expected values of the percentage of authors in alphabetical order are essentially identical, meaning that bioRxiv authors do not deliberately list authors in alphabetical order. This substantiates the argument that bioRxiv preprints use the authorship convention that places the principal investigator last, the author who did most

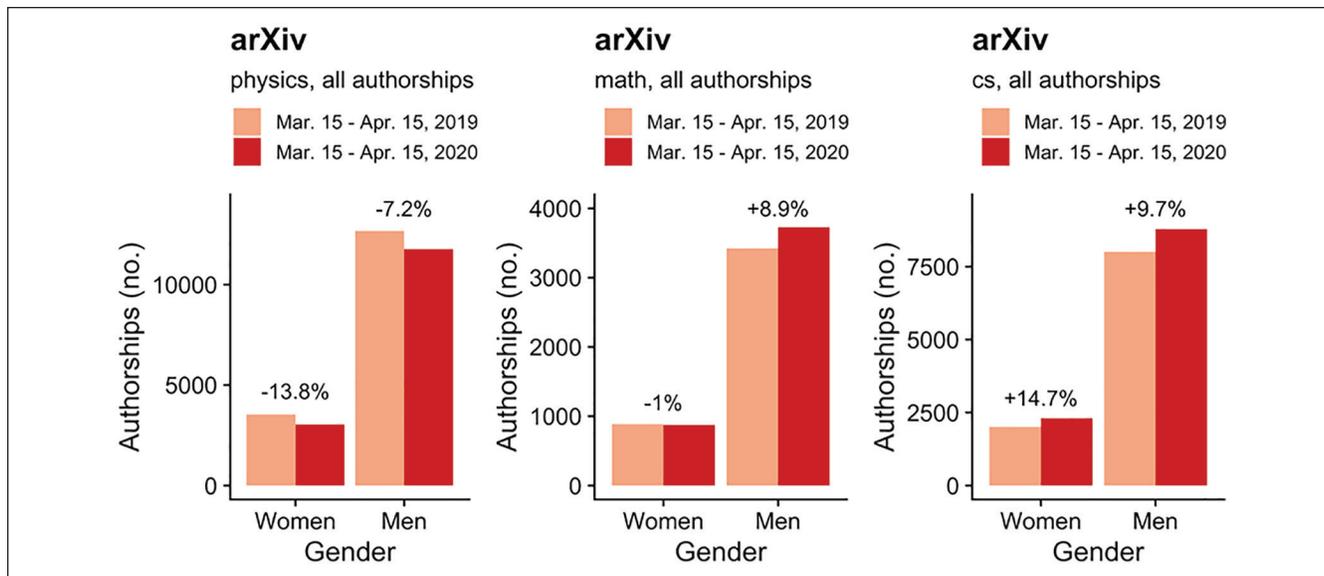


Figure A3. Women versus men authorships in all authorship positions of arXiv preprints in physics, math, and computer science (cs) from March 15 to April 15, 2020, and March 15 to April 15, 2019. Percentages above bars show percentage change year over year for each author position and gender.

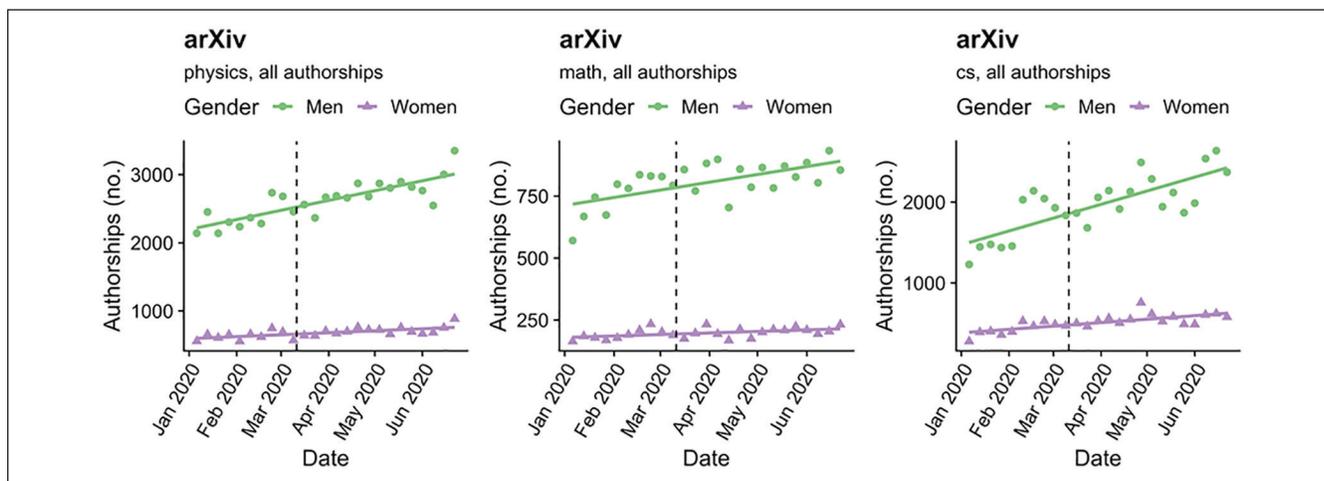


Figure A4. Women (purple triangles) versus men (green circles) in all authorship positions of arXiv preprints in the fields of physics, math, and computer science in the first half of 2020. Each dot is the sum of authorships for one week. The dashed vertical line is March 11, 2020, the day the World Health Organization declared coronavirus disease 2019 a pandemic. Solid lines are simple linear regressions for visualization purposes.

work first, and everyone else in the middle. In contrast, in arXiv, more preprints have authors in alphabetical order than are expected by chance alone, meaning sometimes authors are indeed listed in alphabetical order deliberately (i.e., by convention).

Figures A3 and A4 show the year-over-year and early 2020 analyses, respectively, for the arXiv fields of physics, math, and computer science. As discussed in the main text, the year-over-year analysis (Figure A3) displays a general pattern of less rapid growth in the number of women than men authorships in physics and math;

in computer science, the growth in women authorships outpaced that of men authorships in relative (but not absolute) terms.

During the pandemic, the number of men authorships has grown faster than the number of women authorships in physics, math, and computer science (Figure A4, Table A1). We also checked what the early 2020 models predict for the four other fields in arXiv (results not shown, but see the GitHub repository at <https://github.com/drfreder/king-and-frederickson>). Although the absolute numbers of preprints in these other fields are fairly small (Figure A1), limiting

Table A1. Table of Coefficients Estimated by Linear Models for arXiv Preprint Authorships (All Author Positions Combined) per Day in Physics, Math, and Computer Science.

	Physics	Math	Computer Science
Intercept	3.841***	3.399***	4.413***
Gender	8.191***	4.961***	6.944***
Date	.008***	.003*	.012***
Monday	7.573***	2.562***	4.434***
Tuesday	7.737***	2.434***	4.293***
Wednesday	6.854***	2.345***	3.774***
Thursday	6.907***	2.302***	4.051***
Friday	5.907***	1.707***	3.288***
Saturday	-.344	-.780***	-.223
Gender \times date	.011**	.004*	.012***

Note: Coefficients are not back-transformed from the square-root scale. Reference groups are women and Sunday. A positive gender \times date coefficient means that men authorships are growing faster than women authorships.

* $p < .05$. ** $p < .01$. *** $p < .001$.

the conclusions we can draw from the data, there are significant gender \times date interaction terms for economics (including quantitative finance) and for electrical engineering and systems science. In other words, there is a steeper increase in men than women authorships between January 1 and June 30, 2020. However, for statistics and quantitative biology, the estimates are still positive, but not significant. The nonsignificant gender \times date effect for quantitative biology is consistent with the bioRxiv results: in both data sets (arXiv and bioRxiv), all authorships in biology do not show a significant date \times gender interaction.

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Data, Code, and Analyses

The R code and data for all of our analyses is available on GitHub at <https://github.com/drfreder/king-and-frederickson>.

Supplemental Material

Supplementary data and website records are available on the Open Science Framework repository for this project at <https://osf.io/z2dey/>.

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