The Pandemic Penalty: The gendered effects of COVID-19 on scientific productivity

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1 Abstract

Academia provides a valuable case study for evaluating the effects of social forces on workplace productivity, using a concrete measure of output: the scholarly paper. Many academics – especially women – have experienced unprecedented challenges to scholarly productivity with the onset of the COVID-19 pandemic. In this paper, we analyze the gender composition of over 450,000 authorships of scholarly preprints in the preprint repositories arXiv and bioRxiv from before and during the COVID-19 pandemic. This analysis reveals that the underrepresentation of women scientists in the prestige last authorship position necessary for retention and promotion is only getting more inequitable. We find differences between the arXiv and bioRxiv repositories in how gender affects first, middle, and sole authorship submission rates before and during the pandemic. In a second contribution, we review existing research and theory that could explain the mechanisms behind this widening gender gap in productivity during COVID-19. Finally, we aggregate recommendations for institutional change that could help ameliorate challenges to women's productivity during the pandemic and beyond.

2 Introduction

The COVID-19 pandemic caused myriad social changes throughout society, including the academy. Reports of reduced productivity for faculty – both anecdotal and data-driven – draw our 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 and promotion in faculty careers, academia makes for an excellent case study of how an exogenous shock affects institutional practices.

Many of these changes are disproportionately impacting the productivity of women academics.[1] Women academics face disproportionate work-life balance challenges during the pandemic and are more likely to have reduced their research hours than men (Myers et al., 2020). As we will discuss in more detail in the discussion, there are several possible reasons for this. Because the COVID-19 pandemic has resulted in widespread school and day care 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. At work, women faculty are likely to perform more service, exert more emotional labor, and spend more time transitioning to online learning. Our paper 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 to explain why these differences might be occurring.

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). Though 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, Corbett, & St. Rose, 2010). Furthermore, scientific fields have power, authority, and status in our modern society – as do the scientists who work in them (M. F. Fox, Whittington, & Linkova, 2017). The demographics of those who produce knowledge shape not only the knowledge that is produced (Campbell, Mehtani, Dozier, & Rinehart, 2013), but also the characteristics of people society views as powerful and important.

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 many STEM fields. Peer review takes time, so it is still too soon to see the full effect of COVID-19 on the numbers of journal articles published by women versus men academics. However, a growing number of academics make their submitted or in-progress manuscripts available on preprint servers (Penfold & Polka, 2020), making it possible to measure the pandemic's effect on preprint submissions in real time. 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 still remain significantly underrepresented in faculty positions, particularly tenured positions (Snyder, Brey, & Dillow, 2019). And more highly educated women in the U.S. are now becoming mothers than in the past; 80% of women with doctorates or professional degrees aged 40 and over are mothers, up from 65% only twenty 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 & 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).

Our introduction continues by reviewing why studying academic publishing during the

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

pandemic provides a valuable case for analyzing shocks to social support. We then review existing work on gender gaps in productivity before and during the pandemic. Next, we analyze data from two preprint repositories to assess the gendered publication gap in STEM. We continue with discussion of what structural features of academia and households might have contributed to the observed patterns, and conclude with an extensive discussion of ideas for how these possible explanations could inform university policy.

2.1 A Case Study in Shocks to Professional Support

Not only is this a moment in time that has the potential to affect the careers of a generation of scholars, it is also an important natural experiment in the disruption of work-life routines. Never before in modern history has the entire professional workforce experienced such a dramatic shift in routine. This kind of instrumental variable allows a unique view into the society-wide dynamics of work-life that have previously only been accessible through shocks to individual lives (Newhouse & McClellan, 1998).

Academic careers make a particularly valuable case study because the requirements for promotion are very clear and measurable, compared to other white collar professions. Publication is a concrete, measurable 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, & Klavans, 2014). Analyzing preprint productivity provides insight not only into the challenges for this generation of academics, but the ever-present supports underlying the productivity of professionals.

The ongoing productivity of academics and other white-collar workers presumes a foundation of smoothly running care work and support in the home. This assumed support system allows the "ideal worker" to work long hours without concern for family obligations (Misra, Lundquist, & 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 dramatically from this ideal (by choice or necessity) are challenged with unrealistic expectations for promotion, retention, or tenure (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 (Wayne & Cordeiro, 2003).

Long before the COVID-19 pandemic, multiple studies assessed gender differences in research productivity among academics, with somewhat mixed results (Long, 1992; Xie & Shauman, 1998). Some studies have found that the gender gap in productivity has decreased over time and disappeared in the youngest generation of researchers (van Arensbergen, van der Weijden, & van den Besselaar, 2012), suggesting that academia had been making progress towards greater gender equity in publishing. Multiple pre-pandemic studies have also evaluated the effects of marriage, the presence and age of children, and the timing of parenthood on productivity (Cole & Zuckerman, 1987; M. F. Fox, 2005; Kyvik & Teigen, 1996). Generally speaking, women academics spend more time on childcare and housework, which disproportionately affects their productivity.

2.2 Gender Differences in Productivity during the Pandemic

It has been less than a year since the SARS-CoV-2 virus spread around the world. In this short time span, multiple analyses have assessed the differential impact of the pandemic on men and women academics. However, most of these analyses are preliminary and draw on limited data. Published in the 'grey' literature (e.g., reports, evaluations, news articles, or blog posts) or on preprint servers, they are not yet peer-reviewed.

Several large-scale analyses have suggested that the pandemic is widening the gender gap in academic publishing, in some cases substantially. An analysis of working papers and randomized controlled trials in economics found decreases in submissions by women authors in March and April 2020, accounting for seasonal and yearly changes (Shurchkov, Deryugina, & Stearns, 2020). A working paper looking at over 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. These effects were more pronounced among higher-ranked universities, and in certain fields (Cui, Ding, & Zhu, 2020). A study of the preprint repositories medRxiv and bioRxiv and select Springer-Nature journals showed a drop in women's publishing during the pandemic; these gaps are exacerbated in less wealthy countries (Muric, Lerman, & Ferrara, 2020). Another analysis of 1.2 million authors from 307,459 preprints and registered reports found the largest reductions in submissions by women in the NBER, 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 to both February 2020 and March-April 2019 (Vincent-Lamarre, Sugimoto, & Larivière, 2020). Analysis of 60,000 journals showed a dramatic collapse in women first-authorship in May, 2020, by seven percentage points relative to 2019 (Matthews, 2020). Additionally, studies have found significant gender gaps in authorship on COVID-19 related research (Amano-Patiño, Faraglia, Giannitsarou, & Hasna, 2020; Andersen, Nielsen, Simone, Lewiss, & Jagsi, 2020; Gabster, van Daalen, Dhatt, & Barry, 2020; Pinho-Gomes et al., 2020). Only one analysis of submissions to a single journal found minimal or no gender differences in productivity during the early days of the pandemic (Dolan & Lawless, 2020).

Again, however, most of these studies have not yet been peer-reviewed. Furthermore, the effects shown in these analyses are likely conservative because many preprints describe research completed months ago, long before the COVID-19 pandemic. Nonetheless, they provide us insight into the gap in productivity that is to come. Preprints are warning signals as the challenges of working from home build up and differentially impact men and women.

Here, we add to these studies by extending analyses of the pandemic-affected period through the end of June, 2020. This should provide time for preprint outputs to reflect the effect of lockdown orders, which began in March in many parts of the world. These data also provide an early glimpse into the summer season productivity gap of academics affected by ongoing institutional changes, discussed below. Finally, we discuss possible mechanisms for a gendered impact of COVID-19 on academics, and provide recommendations for universities and other institutions looking to address the pandemic's unequal impacts going forward.

3 Methods

3.1 Compiling the Dataset

We quantified how the COVID-19 pandemic is affecting the gender breakdown of preprint submissions to arXiv and bioRxiv. bioRxiv is a preprint server for biology maintained by Cold Spring Harbor Laboratory. Run by Cornell University, arXiv is a preprint server mainly for physics, math, computer science, and statistics, but 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 & Broman, 2019) and *rbiorxiv* (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-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 world-wide 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% of the world's school children), and this number quickly grew to 1,577 million children (90% of the world's school children) by April 15, 2020 (UNESCO Institute for Statistics, 2020), before declining somewhat in late April as certain countries or states re-opened schools. For comparison, we also scraped submission data for the same dates the previous year, i.e., March 15-April 15, 2019 (inclusive), before the pandemic.

Next, we expanded the date range to scrape all the preprint submission data for Jan 1, 2020 to June 30, 2020 (inclusive), to monitor changes in the gender breakdown 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. As of June 30, 2020, 1,067 million children remain out of school (61% of the world's school children) (UNESCO Institute for Statistics, 2020).

We completed two complementary analyses. The year-over-year analysis – comparing March-April 2020 to March-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-April 2019 happened to be aberrant (i.e., in case there happened to be unusual productivity by men or women academics in March-April 2019). The analysis of January-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-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 their gender (see below), but the bioRxiv API returned first names only for corresponding authors. One of us (MEF) 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, Zhu, Jahn, Boettiger,

& Ram, 2020) to look up each Digital Object Identifier (DOI) and download the citation in BibTeX format, which included first and last names for all authors. This work-around 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, Bergstrom, Correll, Jacquet, & West, 2017), we include authors who submitted multiple preprints, not only unique authors. Thus, an *authorship* is an author on a single paper.

3.2 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 to names in a database; we used the U.S. Social Security Administration baby names database. The R *gender* package matches names based on 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 found that including datasets 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 dataset, 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 datasets. 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, R. Sugimoto, & Larivière, 2020; West, Jacquet, King, Correll, & Bergstrom, 2013).

3.3 Summary Statistics and Modeling Approach

There were 149124 preprints in the dataset we assembled: 114632 arXiv preprints and 34492 bioRxiv preprints. These preprints had a total of 808227 non-unique authorships; 549512 arXiv authorships and 258715 bioRxiv authorships. Some individuals authored more than one preprint in the dataset.

We inferred the gender of 266133, or 48.4%, of arXiv authors and 195204, or 75.5%, 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 datasets (Wais, 2016).

Using the data from January 1 - June 30, 2020, we modelled the number of preprint authorships per day as a function of submission date and gender.[2] 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 dataset (i.e., arXiv, 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 (J. Fox & Weisberg, 2019) in R to calculate ANOVAs with type III sums of squares.

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

4 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 on men as first authors of bioRxiv preprints.

4.1 Year-over-year comparison of arXiv preprint submissions

We began by comparing arXiv preprint authorships between March 15-April 15, 2020, during the COVID-19 pandemic, to 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 & 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 impacting experimental scientists. Nonetheless, there were 14978 submissions to arXiv between March 15 and April 15, 2020, compared to 13733 submissions in the same date range in 2019, an increase of 9.1%.

[2]Note that although many more preprints are submitted to arXiv than bioRxiv every day, since 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.

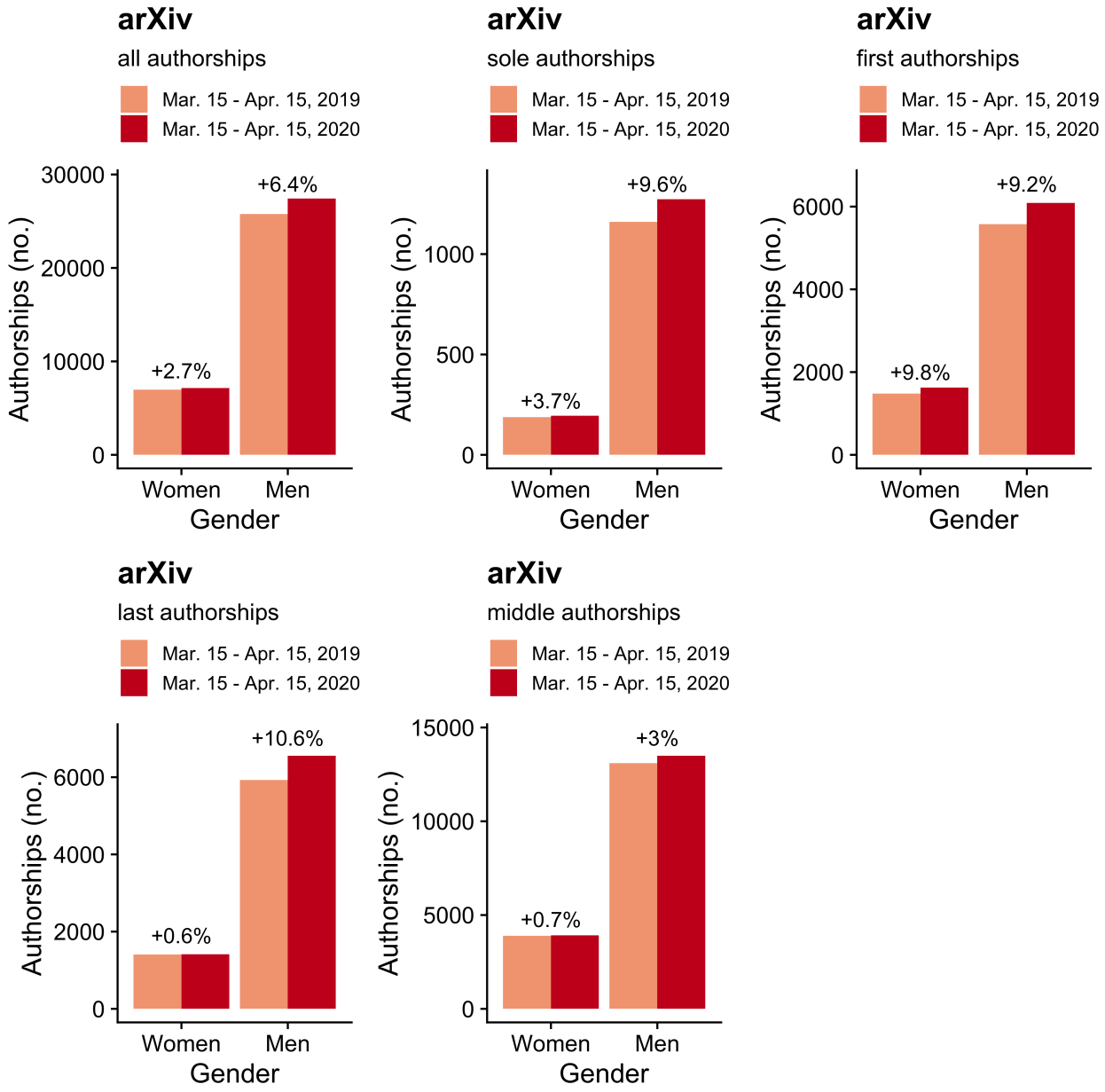

Figure 1: Women versus men authorships of arXiv preprints from March 15-April 15, 2020 and March 15-April 15, 2019. First, middle, and last authorships are for multi-authored preprints only. Percentages above bars show percent change year-over-year for each author position and gender.

While 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 1648 authorships and women added 189 authorships in March/April 2020 compared to March/April 2019, corresponding to increases of 6.4% and 2.7% for men and women, respectively. Put differently, in March/April 2019, 78.7% of arXiv authorships were men, but 89.7% of the additional authorships in 2020 were men. Next, we separately analyzed the data for preprints with a single author, and for first, middle, and last authorships of multi-authored preprints. There were 112 more preprints sole-authored by a man but just 7 more preprints sole-authored by a woman in March/April 2020 than in March/April 2019, representing increases of 9.6% and 3.7%, respectively (Figure 1). In contrast, there were 514 more men first authorships and 145 more women first authorships in March/April 2020 than in March/April 2019, or a 9.2% and a 9.8% increase, respectively. In other words, in absolute terms, there was a greater increase in men than women first authorships of multi-authored arXiv preprints between March/April 2019 and March/April 2020, but women made slightly greater gains than men in the first author position when measured as a percent change, year-over-year. However, women lagged behind men in gains as middle and last authors of multi-authored papers. Specifically, there were 627 more men last authorships but only 8 more women last authorships between March/April 2019 and March/April 2020. This represents a 10.6% increase in men last authorships, while women last authorships are essentially unchanged over the same period, having grown just 0.6%. Finally, the number of women middle authorships rose by 29 from March-April 2019 to March-April 2020, a change of just 0.7%, while the number of men middle authorships rose by 395, or 3%. In summary, except for first authorships, men made greater gains than women as arXiv preprints authors during the pandemic, compared to the same dates the previous year. Furthermore, the gender gap is growing fastest among last authors.

4.2 arXiv 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 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. For the arXiv dataset, the pattern of women making smaller authorship gains during the pandemic than men holds across all authorship positions, but with varying effect sizes (Figure 2, Table 1).

Again, during the pandemic, the number of men authorships has grown faster than the number of women authorships, visible in Figure 2 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 x date interaction effect. Gender always had a significant main effect, which simply means that there were always significantly more men authorships than women authorships at the

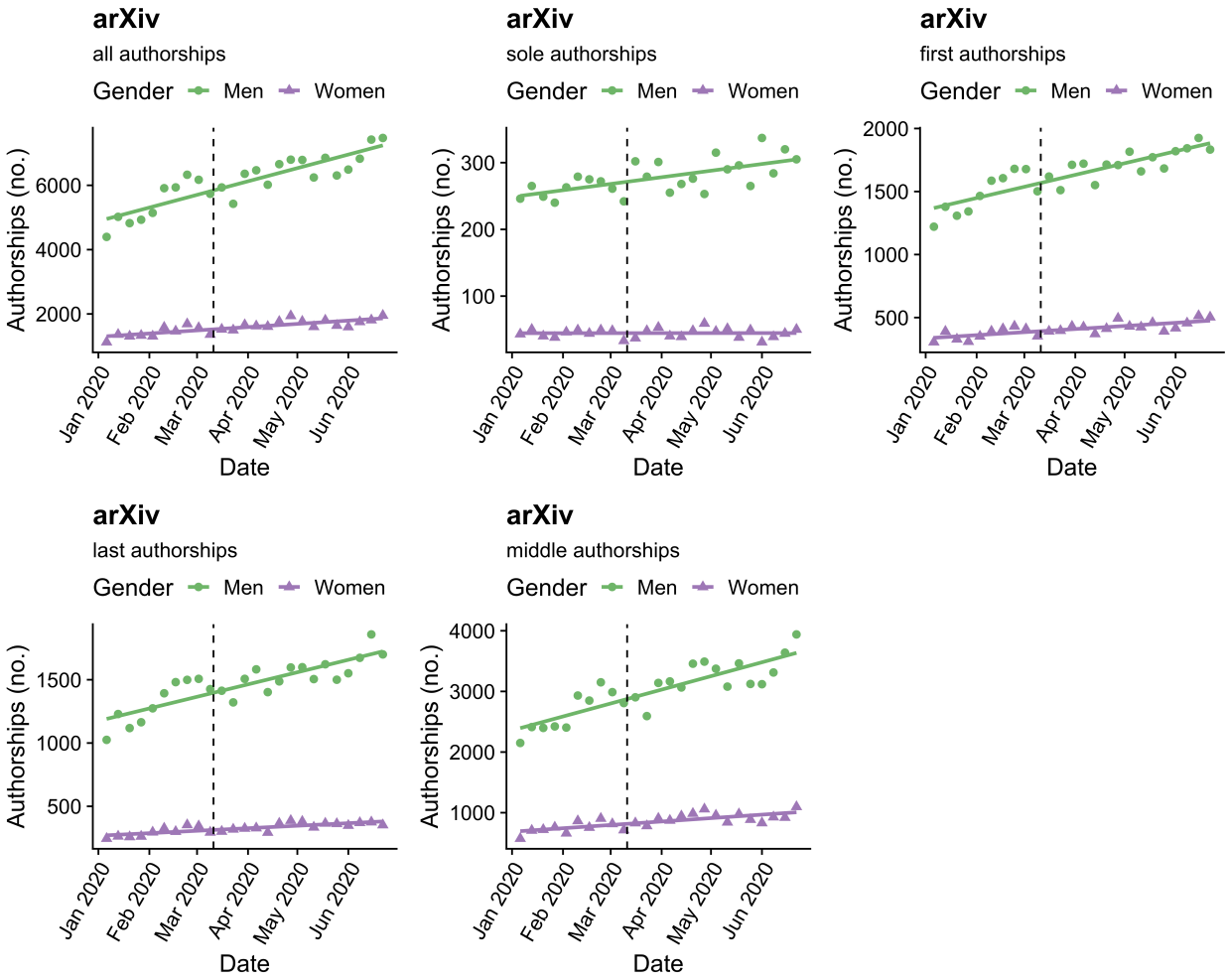

Figure 2: Women (purple triangles) versus men (green circles) authorships of arXiv preprints in the first half of 2020. Each dot is the sum of authorships for one week. First, middle, and last authorships are for multi-authored preprints only. The dashed vertical line is March 11, 2020, the day the World Health Organization declared COVID-19 a pandemic. Solid lines are simple linear regressions for visualization purposes; see Table 1 for results of statistical models.

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 and see also Figure 2). The gender x 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. For all five authorship categories (all authorships combined, sole authorships, and first, last, and middle authorships on multi-authored preprints), there was a significantly positive gender x 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.

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	0.016***	0.001	0.008***	0.007***	0.012***
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***	0.622***	3.221 ***	3.075***	5.357***
saturday	-0.777	-0.471***	-0.549*	-0.355	-0.441
gender x date	0.018***	0.003**	0.008***	0.009***	0.013***

Coefficients are not back-transformed from the square-root scale. References groups are women and Sunday. A positive gender x date coefficient means men authorships are growing faster than women authorships. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

4.3 Year-over-year comparison of bioRxiv preprint submissions

We sought to compare fields by conducting 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

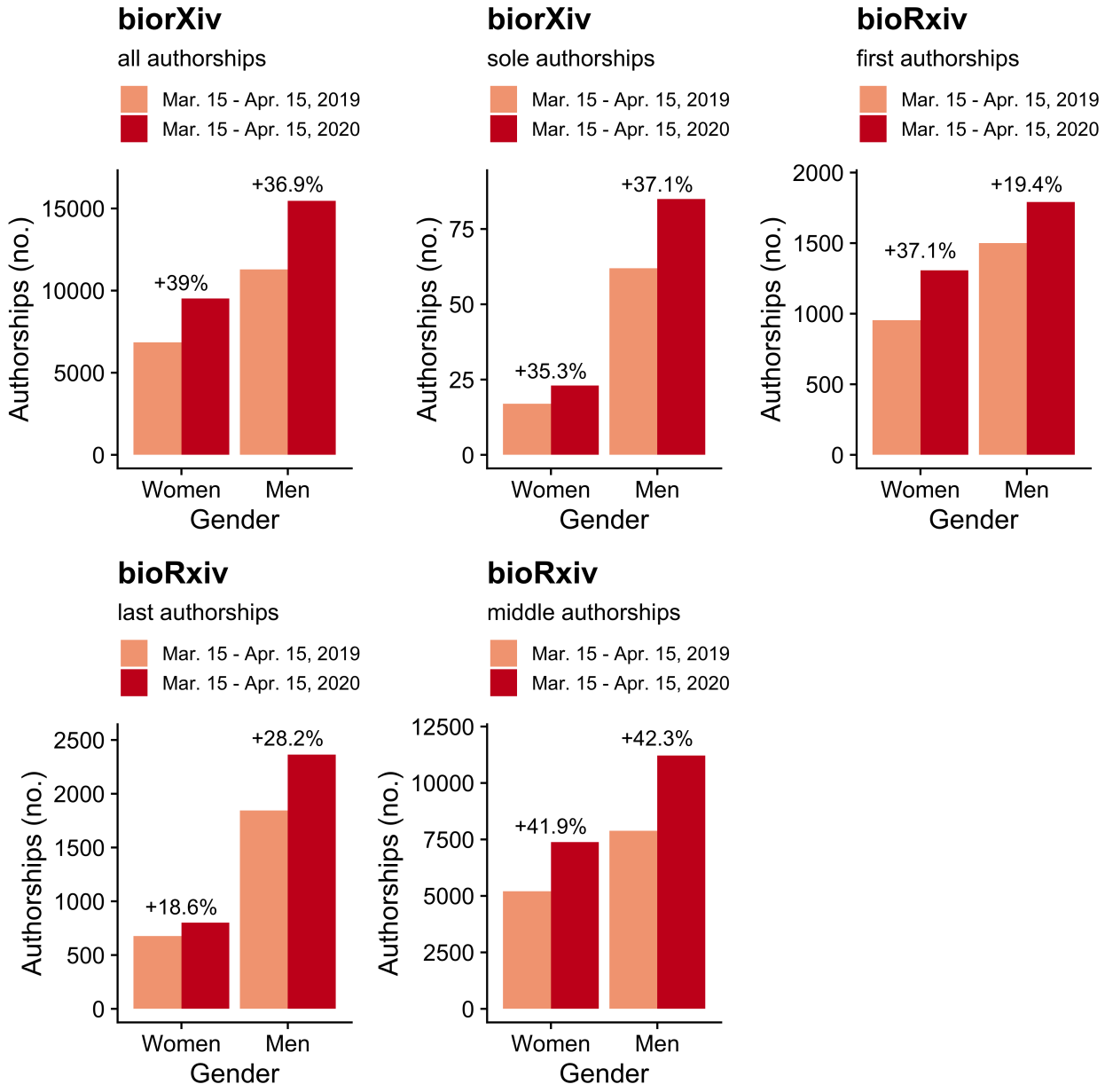

Figure 3: Women versus men authorships of bioRxiv preprints from March 15-April 15, 2020 and March 15-April 15, 2019. First, middle, and last authorships are for multi-authored preprints only. Percentages above bars show percent change year-over-year for each author position and gender.

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 3381 preprints between March 15 and April 15, 2019 to 4437 preprints over the same dates in 2020, an increase of 31%. Across all author positions, women authorships have actually increased a little more than men authorships year-over-year, as a percent change. In absolute terms, there were 2669 more women authorships compared to 4168 more men authorships in March/April 2020 than in March/April 2020, representing increases of 39% and 36.9%, respectively (Figure 3). 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 multi-authored preprints. Both as a percent 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%) and 291 men first authorships (19.4%) in March/April 2020, compared to the same dates in 2019.

In contrast, sole, middle, and last authorships all increased faster for men than women, although there is only a large gender difference for the last author position. Women submitted 6 additional sole-authored preprints to bioRxiv (up 35.3%) in March/April 2020, compared to March/April 2019, while men submitted 23 more sole-authored preprints (up 37.1%); however, the absolute numbers are small, limiting the conclusions we can draw from these data. There was also just slightly more growth among men than women middle authorships, with an additional 2183 women middle authorships and 3334 men middle authorships between March/April 2019 and 2020, representing percent gains of 41.9% and 42.3%, respectively. But while women essentially 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/April 2019 and 2020, increases of 28.2% and 18.6%, respectively (Figure 3).

Thus, compared to 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 pre-pandemic trends towards greater gender equity. These findings, however, are complicated by our analyses of the first six months of 2020 in the next section.

4.4 bioRxiv preprint submissions immediately before and during the COVID-19 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 six months

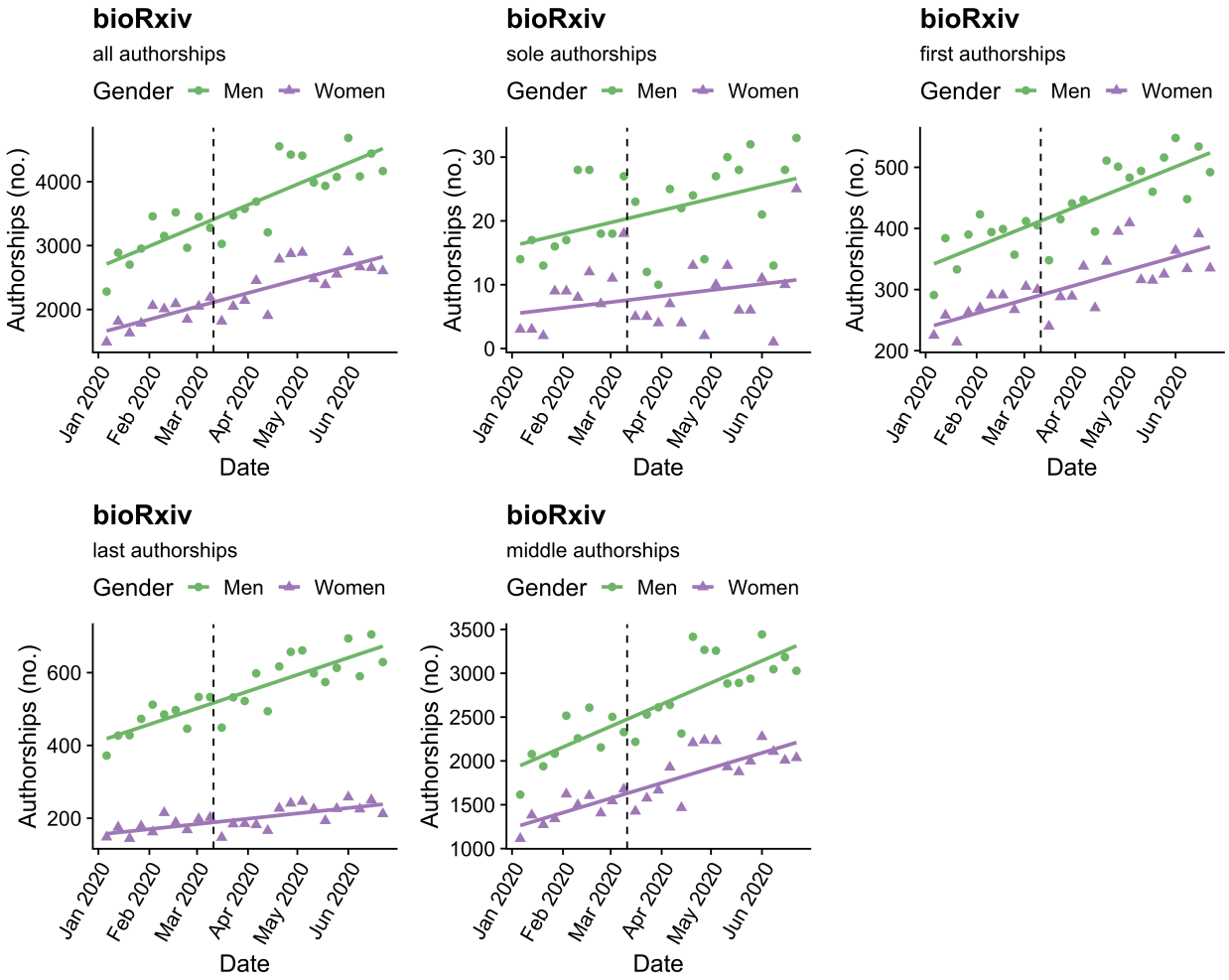

Figure 4: Women (purple triangles) versus men (green circles) authorships of bioRxiv preprints in the first half of 2020. Each dot is the sum of authorships for one week. First, middle, and last authorships are for multi-authored preprints only. The dashed vertical line is March 11, 2020, the day the 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.

for both genders, significantly so for all author positions except sole authorships (Table 2). However, there are no significant gender x 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 3), 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 and Figure 4). This implies 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 x 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.

Table 2: Table of coefficients estimated by linear models for bioRxiv preprints per day.

	all	sole	first	last	middle
intercept	9.678***	0.472**	3.687***	2.691***	8.510***
gender	4.072***	0.806***	1.125***	2.833***	3.087***
date	0.033***	0.001	0.011***	0.008***	0.030***
monday	3.599***	0.104	1.362***	1.306***	3.071***
tuesday	6.111***	0.295	2.316***	2.271***	5.175***
wednesday	6.077***	0.256	2.215***	2.151***	5.229***
thursday	7.660***	0.276	2.857***	2.784***	6.549***
friday	6.753***	0.068	2.490***	2.489***	5.782***
saturday	2.440**	0.053	0.865**	0.854**	2.125**
gender x date	0.007	0.001	0.001	0.006*	0.005

Coefficients are not back-transformed from the square-root scale. References groups are women and Sunday. A positive gender x date coefficient means men authorships are growing faster than women authorships. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

4.5 Comparison: arXiv and bioRxiv

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, there was a significant reduction in women authorships in the first, middle, last and sole author positions; we found no such effect in the bioRxiv repository. We cannot determine the reason for this difference between the repositories, though it is not a problem of statistical power.

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. Our results differ from published studies in two notable ways. Vincent-Lamarre, Sugimoto, and Larivière (2020) found that the proportion of first authorships by women in bioRxiv and arXiv remained steady. 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, since 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 co-authorships and author order.

Overall, we find significant reductions in the rate of increase in preprint submissions to arXiv for all authorship positions by women and to bioRxiv for last authorships by women during the COVID-19 pandemic. There is a growing gender gap during the pandemic for all authorship positions in arXiv. Though the year-over-year analyses produce mixed conclusions for bioRxiv, we have unambiguous evidence to support the hypothesis that the rate of submission of bioRxiv preprints by women in last authorships has been negatively affected by the pandemic.

5 Possible Explanations

While our analysis does not allow us to distinguish among several possible mechanisms for the observed patterns in the data, our results are consistent with an extensive literature on gender-based productivity differences. While we could not test these potential explanations, previous research on the mechanisms underlying gender gaps in productivity can help illuminate the trends we have observed in the preprint servers during the pandemic. This includes the facts that women academics are disproportionately responsible for child care and household work, more likely to be in a dual-career relationship with another academic, and have more service and teaching responsibilities. Of course, there could be other possible mechanisms that explain the productivity gap.[3] The true cause is likely some combination of these. In this second major contribution, we discuss each of these five potential explanations

[3]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, while epidemiology has seen a huge surge of preprint submissions, it is a field with relatively equal gender ratios of practitioners before the pandemic (Schisterman, Swanson, Lu, & Mumford, 2017). Alternatively, women might be a part of collaborations that are harder to carry out during COVID-19 restrictions. This potential alternative explanation is unlikely since women scientists are less likely to collaborate than men (Kyvik & Teigen, 1996), though this does vary somewhat by field and cohort (McDowell & Smith, 1992; Ozel, Kretschmer, & Kretschmer, 2014; Rhoten & Pfirman, 2007). 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.

in more depth. We then turn to implications for university policy.

5.1 Childcare in the Pandemic

Many countries and states closed schools and childcare centers to slow the spread of COVID-19, such that 90% of the world's school-aged children were out of school on April 15, 2020, and many have still not returned to school at the time of writing. 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 is thus one possible explanation for the growing gap in productivity during the pandemic. Furthermore, 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; in the sciences, last authors are generally principal investigators who head up labs, while first authors are often graduate students or postdoctoral researchers. Because academic women typically have children fairly late into their child-bearing years (Mason & Goulden, 2004), women principal investigators are more likely to have young children at home than women graduate students or postdocs.

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 U.S., men tenure-track professors are actually more likely to have children living in the household than same-stage women.[4] In the 2017 NSF Survey of Doctorate Recipients (*Survey of Doctorate Recipients 2017*, 2019), 44% of men assistant professors reported having children in their households, compared to 40% of women assistant professors. This gap remains consistent at the associate professor level – with 46.1% men and 42.6% of women – and at the full professor rank, with 36.6% of men and 30.1% 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% of women and 29.5% of men have children at home.[5] However, people with these positions are likely responsible for only a small number of preprint submissions, since their jobs focus primarily on teaching (although some still make important, but often unpaid, contributions to scientific research).

Even with these small and sometimes favorable gaps, women scientists are responsible for the majority of childcare responsibilities in the home (Schiebinger & Gilmartin, 2010). Women do over 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 & Gilmartin, 2010). Women faculty with children spend over 15 more hours on caregiving activities per week than their men colleagues (Mason, Stacy, Goulden, Hoffman, & Frasch, 2005). Among early-career physician-researchers funded by the National

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

[5]We generated these summary statistics using the publicly available 2017 NSF Survey of Doctorate Recipients on the Scientists and Engineers Statistical Data System (*Survey of Doctorate Recipients 2017*, 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.

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 institutions finds that while both men and women report that work interferes with family more than the reverse, women report more conflict in both directions (M. F. Fox, Fonseca, & Bao, 2011). Furthermore, all these studies were conducted before the COVID-19 pandemic, when parents could avail themselves of 'normal' childcare options.

The proportion of parents who report they share domestic chores equally has increased since before the pandemic. As a result, the fraction of families where mothers are primarily responsible for household labor has decreased substantially. However, 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, & Pepin, 2020). The childcare burden is even greater for single parents, who in Canada, for example, make up 20% of families with children under 16. Women make up 81% these single-parent householders (*Lone-parent families*, 2015).

Pre-pandemic findings on the effects of children on academic productivity have been mixed, though the most recent studies find a negative effect of having (especially young) children at home on women's research productivity. Although one study found women scientists with preschool 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 (M. F. Fox, 2005). Other research finds that 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 & Teigen, 1996). Another longitudinal study found a one-time positive effective 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, with a larger productivity penalty for mothers (Hunter & 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 to 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 are spending even less time on research, relative to men, and it is unlikely that these other mitigating factors are having a helpful effect. In a survey of U.S. and European principal investigators during the pandemic, scientists with young children reported a 17% larger reduction in research time compared to scientists without a young dependent, all else equal. This is separate from a 5% larger decline in research time reported by women scientists, all else equal (Myers et al., 2020).

Of course, gender and parenthood status are not perfectly predictive of increased caregiving demands during the pandemic.[6] Some men academics are primary caregivers for their

[6]Children 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 & Drago, 2000).

children, and many women academics do not have children at home. But even when men and women academics both have young children at home, men's careers are less likely to be adversely affected (Mason et al., 2013). Even among parents who report splitting 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.

5.2 Balancing Domestic and Paid Work

Another possible explanation for the growing productivity gaps we observe is increased difficulty balancing domestic and paid work, particularly for women academics. Women scientists, on average, are less likely to have full-time support at home, a trend that likely has been exacerbated by the pandemic.

In 2008, a survey found that men academics were four times more likely to have a stay-at-home partner than were women academics (Schiebinger, Henderson, & Gilmartin, 2008). Layoffs and furloughs due to the economic downturn associated with COVID-19 have disproportionately affected women workers (Alon, Doepke, Olmstead-Rumsey, & Tertilt, 2020; Cottom, 2020). As a result, it is likely that even more men than the 20% reported in the 2008 survey (conducted during a time men were statistically more likely to be out of work) will currently have stay-at-home partners.

Furthermore, when a couple is considering who might quit or reduce work hours in order to account for increased at-home childcare demands, even an ideologically egalitarian couple will choose the lower earner to stay home (Risman, 1998).[7] Non-academic women partners may have voluntarily stayed home or reduced work hours more often than men during the early days of 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, Landivar, Ruppanner, & Scarborough, 2020). Additionally, men are already more likely to have partners who do not work outside the home. If anything, we expect this disparity would have increased in recent months. 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 & Gilmartin, 2010).

5.3 Dual Career Academics

The third possible explanation for the growing gender gaps we find in academic productivity is a special case of the first two: women academics are more likely than men to be in a relationship with another academic, giving them statistically less working time on average.

Women are more likely to be partnered with another academic. This is even more true in the natural sciences, where 48% of women have an academic partner compared to 35% of

However, time tracking studies have found no difference in faculty time spent on elder care (Misra et al., 2012).

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

men (Schiebinger et al., 2008). In academic couples, 83% of women scientists but only 54% of men scientists are coupled to another scientist (Schiebinger et al., 2008). In dual-academic couples, women academics still do a far greater share of all household duties. However, academic women in a couple with another academic man have slightly more egalitarian sharing of household duties than academic women in other types of relationships (Schiebinger & 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 affects the 48% of women scientists in the life sciences – but only 35% of men scientists – with academic partners. The remainder of men scientists (65%) do less than half of the childcare, while the remainder of women scientists (52%) likely 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. [8] Statistically, among all academics, women are going to be less productive. Add to this that women in dual-academic couples are more likely to place equal value on their and their partner's careers than are men in a dual-academic couple (Schiebinger et al., 2008). Given this imbalance, women academics may find their time less protected then that of their partners'.

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 labour and child care 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 child care work in their households, to compensate for the large number of households where men and women have traditional gender roles. Gender equality in academia cannot rely on the coordinated behavior of thousands of households, so we point to institutional solutions later on.

5.4 Service

A fourth potential mechanism that might explain the reduced rate of submission among women authorships is an increase in service expectations during the pandemic. In a survey of tenured and tenure-track faculty 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 on service, with women full professors reporting notably more time spent on service than men professors (Guarino & Borden, 2017).

The advent of the pandemic also created needs for universities to develop both short-term 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 – another form of internal university service. Since the gender gap in service time is driven primarily by internal service (Guarino & Borden, 2017),

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

this increased need may have only exacerbated the demands on women faculty's time during the COVID-19 pandemic.

5.5 The Transition to Online Teaching

The fifth potential mechanism suggested by previous research that may explain the gap in gender productivity rates is the corresponding gender gap in teaching. 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, Lundquist, Holmes, & Agiomavritis, 2011). Women are less likely to hold positions at research universities, and more likely to be in adjunct or other temporary teaching roles (Finkelstein, Conley, & Schuster, 2016; Monks, 2009; Steinþórsdóttir, Einarsdóttir, Heijstra, Pétursdóttir, & Smidt, 2018). Research suggests that online teaching takes more time, especially when initially creating a class, than in-person teaching (Kenny & Fluck, 2017; Myers et al., 2020; Tomei, 2006). In the spring corresponding with 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 would have created greater demands on the time of those faculty with larger teaching responsibilities. Since these are disproportionately women, the reduced research productivity of women during the shelter-at-home orders may be due in part to increased teaching demands.

Furthermore, women are generally expected to perform more emotional labor in the classroom than men (Bellas, 1999). This involves more outreach to under-performing students and more time spent in office hours supporting students' personal and psycho-social development (El-Alayli, Hansen-Brown, & Ceynar, 2018). Women faculty, and particularly women of color faculty, must engage in a disproportionate amount of emotional labor for the university, especially for required diversity courses (Moore, Acosta, Perry, & Edwards, 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 beyond curriculum development.

6 Implications

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). 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 & Ebensperger, 2020), it is crucial that universities provide institutional support for the unique challenges of this moment. In this third section of the paper, we outline research-based solutions institutions can implement to counteract the challenges women faculty face during the pandemic.

6.1 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 pre-existing inequities because of the unequal disease burden (Williamson et al., 2020), racial or ethnic discrimination and bias during the pandemic, and increased emotional labor.

Institutions can reduce bias by ensuring the evaluation process is holistic. 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, Ryan, Moss-Racusin, & Ravetz, 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 a motherhood penalty, whereby women are generally penalized in evaluations for having children (Benard & Correll, 2010; Correll, Benard, & Paik, 2007).[9] Institutions should explicitly not require any teaching evaluations from during the transition period of the pandemic as part of hiring, retention, or promotion materials (Gonzales & 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, since 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 in implementation (Antecol, Bedard, & Stearns, 2018; Manchester, Leslie, & Kramer, 2013; Williams & Lee, 2016). Furthermore, extensions delay the increase in pay and power which come with promotion for both women and men (Manchester et al., 2013). So 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 & Griffin, 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 & Griffin, 2020). Asking committees to completely discount papers written during this period is unrealistic. Institutional shared governance groups need to clarify expectations for productivity with gender equity in mind. Malisch et al. (2020) outline recommendations for how such committees might develop metrics and structures and ensure their institutional adoption.

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

6.2 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 & 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 new productive 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 to facilitate the ongoing involvement of women scholars in COVID-19 policymaking.

6.3 Getting Scientists Back to Work

Taking time out of the labor force for child care has immense professional and economic costs for women – and men (Madowitz, Rowell, & Hamm, 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. 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.

6.4 Supporting Teaching

Rather than attempting to evaluate online learning or teaching efficacy using student evaluations, faculty should be asked to document the move to online teaching using reflections or "before" and "after" syllabi (Gonzales & Griffin, 2020). Faculty can also be invited to document the emotional labor and support provided to students during this time (Gonzales & Griffin, 2020). Moving forward, student life offices can support faculty by providing templates for how to support students with common challenges.

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 should

also consider providing more course releases during this time, even though budgets are tight. This could be administered through a special application-based program, giving early-career mothers (and especially single parents) priority.

6.5 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, Jaeger, Misra, Lennartz, & Kuvaeva, 2018).

Institutions that have diverted university grants should prioritize the return of funding for early career mothers. Universities could provide a flexible spending account so that mothers can hire a caretaker for their children or elderly parents. Flexible spending accounts could also allow spending for housework for all faculty, a benefit which is inclusive and also gender equitable (Schiebinger & Gilmartin, 2010). Additional funds for home-office items can reduce the challenges of working from home with children or other family members.

6.6 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; M. F. 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 partner as often as they are now. Although, unfortunately, 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 child care. 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 post-pandemic and to guard against future exogenous shocks to academic productivity, be they to particular individuals or more widespread, as with COVID-19.

6.7 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 in developing strategic plans and initiatives to support faculty (Rosen & Lester, 2020).

Many of these suggestions will cost money. However, when compared to the substantial investments institutions have previously dedicated to recruiting and retaining qualified women faculty (Williams & 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.[10] The service contributions to such a committee should be documented and valued for retention, tenure, and promotion (Malisch et al., 2020).

For those who might read these suggestions and feel they do not go far enough, 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.

7 Conclusion

Institutions of higher education need to heed these warning signals and take action now to prevent backsliding on gender equity. Women scientists have experienced a productivity penalty from the social and structural changes accompanying the COVID-19 pandemic. However, these widening gaps are not reflected in all authorship positions. Women are experiencing relative productivity declines in last authorship positions in both the arXiv and bioRxiv preprint repositories. However, in the first, middle, and sole author positions, women authorship rates have not been affected by the pandemic in bioRxiv – only in arXiv.

The trends in both preprint servers 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 by time. This analysis could also be extended to examine the effects of author order, field, and researcher institution or country. Understanding this difference between fields amongst first, middle, last, and sole author positions is an area ripe for future research. 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.

Women academics shoulder more responsibility for childcare and domestic work. They 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, & Folbre, 2002; Madowitz et al., 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, women faculty's productivity has decreased during the pandemic.

Women scientists are facing a reduction in relative productivity as a result of COVID-19. This research reveals the under-representation of women scientists in the prestige authorship positions necessary for retention and promotion is only getting more inequitable during the COVID-19 pandemic. Publication productivity has important implications for cumulative advantage and visibility in careers (Fowler & 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.

[10] Suggestions for the operation and recommended actions of such a committee are available at https://academicequity.com (Malisch et al., 2020).

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