

Do researchers preferentially collaborate with same-gendered colleagues?

Luke Holman* and Claire Morandin§

**luke.holman@unimelb.edu.au*

Abstract

Evidence suggests that women in academia are hindered by conscious and unconscious biases, and that many female researchers feel excluded from formal and informal opportunities for research collaboration. In addition to ensuring fairness and helping redress gender imbalance in the academic workforce, increasing women's access to collaboration could help scientific progress by drawing on more of the available human capital. Here, we test whether researchers preferentially collaborate with same-gendered colleagues, using more stringent methods and a larger dataset than in past work. Our results reaffirm that researchers co-publish with colleagues of the same gender, and show that this 'gender homophily' is slightly stronger today than it was 10 years ago. Contrary to our expectations, we found no evidence that homophily is driven mostly by senior academics, and no evidence that homophily is strongest in fields where women are in the minority. Interestingly, homophily was negatively correlated with journal impact factor (standardised by research discipline), as predicted if mixed-gender teams produce better research.

Keywords: Gender bias, Homophily, Scientific collaboration, Text mining, Women in STEM.

*School of BioSciences, The University of Melbourne, Victoria, Australia

§Organismal and Evolutionary Biology Research Programme, Faculty of Biological and Environmental Sciences, University of Helsinki, Finland

Introduction

Women are substantially underrepresented in many branches of the workforce in science, technology, engineering, mathematics, and medicine (STEMM), and face additional challenges and inequities relative to men (e.g. Larivière et al. 2013; West et al. 2013; Elsevier Report 2017; Holman et al. 2018). On average, women occupy more junior positions (Wutte 2007; Reuben et al. 2014) with lower salaries (Trower and Chait 2002; Umbach 2007), receive less grant money (Hosek et al. 2005; Health 2008), are promoted more slowly (Zuckerman 1987; Rosenfeld 1991; Long et al. 1993; Hopkins et al. 2013), and are allocated fewer resources (O’Dorchai et al. 2009) and less research funding (Feldt 1986, Stack (2004), Larivière et al. (2011)) than men. Experimental studies have shown that people regard women’s research achievements less favourably than identical achievements by men (Moss-Racusin et al. 2012; Knobloch-Westerwick et al. 2013).

Because publishing, networking and collaboration are all instrumental to scientific productivity and thus, academic career advancement (Lee and Barry 2005; Wuchty et al. 2007; Abramo et al. 2009; Larivière et al. 2015), dozens of studies have tested for gender differences in these areas (Long 1992; see also Bozeman and Gaughan 2011; Abramo et al. 2013; Badar et al. 2013; reviewed in Table S1 of Holman et al. 2018). For example, studies have shown that relative to men, women tend to be less involved in international collaboration (Lewison 2001; Webster 2001; Bozeman and Elizabeth 2004; Larivière et al. 2011; Abramo et al. 2013), collaborate less with researchers from their own university department (Webster 2001), have less prestigious collaborations (Long 1990), and fewer collaborations in general (Fuchs et al. 2001). These gender differences in collaboration practice presumably have multiple concurrent causes, which might include implicit and explicit gender bias [REFS], differential family obligations (Reskin 1978; Long 1990; Wright et al. 2003), concerns relating to sexual harassment [REFS], lower participation of women in international conferences (Lewison 2001; Eisen 2014; Martin 2014), and reduced receipt of research travel funds by women (Bozeman and Elizabeth 2004).

A high, steadily increasing proportion of research papers is written by more than one author (West et al. 2013), making collaboration a key predictor of publication output, and thus of career prospects (Tower et al. 2007; Jordan et al. 2008; Cohn et al. n.d.). Additionally, empirical studies suggest that mixed-gender (Bear and Anita Williams 2011; Campbell et al. 2013) or otherwise diverse (Hong and Scott E 2004) teams can produce better results on collaborative tasks than less diverse teams. For reasons such as these, several studies have tested for gender differences in collaboration frequency or pattern by examining the author lists of published research. To our knowledge, every published study of this question has concluded that men co-publish with other men, and women with women, more often than expected if collaborators assort randomly with respect to gender (Ferber and Michelle 1980; McDowell and Smith 1992; Crow and Smykla 2015; Ghiasi et al. 2015; Araújo and Elsa 2017a, 2017b; Fahmy and Jacob TN 2017; Jadidi et al. 2017; Teele and Kathleen 2017; Zettler et al. 2017). This pattern of assortative publishing has been termed ‘gender homophily’.

However, we believe that these prior studies of gender homophily were hindered by a largely unacknowledged statistical issue that we term the Wahlund effect (Figure 1), meaning that

the true extent of homophily is difficult to ascertain from current data. Essentially, whenever coauthorship data are sampled from two or more discrete sets of literature, which vary in the author gender ratio and which are largely not connected by collaboration, the number of same-gendered coauthors will be inflated. This can give the impression that authors preferentially publish with same-gendered colleagues if no gender preferences exist, or even if researchers actually prefer opposite-gendered colleagues. For example, a sample of literature containing bioinformatics and cell biology papers will probably contain an excess of mostly-male and mostly-female author lists, simply because researchers preferentially work with colleagues from the same discipline, and because the author gender ratio is more male-biased in bioinformatics than in cell biology (Holman et al. 2018). We chose the name by analogy with the Wahlund effect in population genetics (Wahlund 1928), whereby spatial differences in allele frequencies create an excess of homozygotes across the whole population, even if alleles are randomly assorted within each subpopulation (original idea in BERGSTROM REF).

In the present study, we test whether academics tend to co-publish with same-gendered collaborators, while controlling for the Wahlund effect as strictly as possible. Our study uses a recently-published dataset describing the gender of 35.5m authors from 9.15m articles indexed on PubMed (Holman et al. 2018). Holman et al. (2018) reported large differences in the gender ratio of authors across research disciplines, journals, countries, and across the years 2002-2016. We therefore tested for gender homophily after restricting the analysis to particular journals (i.e. research specialties), time periods, and countries.

Methods

Obtaining author lists and assigning gender

We used the dataset of PubMed author lists from Holman et al. (2018). Briefly, that dataset was created by downloading every single article indexed on PubMed, from the oldest articles up to the present (which was August 2016), and attempting to assign a gender to each author based on their given name, using the web service genderize.io. Each journal was assigned to one of 107 scientific disciplines (e.g. *Nephrology* or *Cell Biology*), using PubMed’s journal categorisations where available. Because the present study focuses on co-authorship, all single-author papers were removed from the dataset. To simplify the statistical analysis, we also discarded all papers for which we could not determine the gender of every author with at least 95% certainty. To mitigate Wahlund effects caused by variation in the gender ratio of researchers over time (see below), we also discarded all papers except those that were published either 0-1 or 10-11 years before the PubMed data were collected (i.e. 20th August 2016). Lastly, we excluded journals with fewer than 50 suitable papers. This left us with a dataset from August 2015 - August 2016 containing 276,879 papers with 1,311,213 authorships, and a dataset from August 2005 - August 2006 containing 151,652 papers and 647,634 authorships. These papers came from 2,116 and 1,192 journals respectively, which were grouped into 107 and 101 research disciplines. There was a median of 87 (87) papers

per journal, 413 (371) authors per journal, and 4 (4) authors per paper (the first number is for 2015-6, and the bracketed number for 2005-6).

Calculating α , the coefficient of homophily

Inspired by Bergstrom et al. (http://www.eigenfactor.org/gender/assortativity/measuring_homophily.pdf), we defined the coefficient of homophily as $\alpha = p - q$, where p is the probability that a randomly-chosen co-author of a *male* author is a man and q is the probability that a randomly-chosen co-author of a *female* author is a man. Therefore, $\alpha > 0$ suggests that same-gender authors publish together more often than expected if authors assort randomly with respect to gender (homophily), $\alpha < 0$ suggests that opposite-gender authors publish together more often than expected (heterophily), and $\alpha = 0$ suggests random assortment with respect to gender.

To estimate α for a particular subset of the scientific literature, we estimated p as the average proportion of men’s co-authors who are men (averaged across all papers with at least one man author), and q as the average proportion of women’s co-authors who are men (averaged across all papers with at least one woman author). To estimate the 95% confidence intervals on α for a given set of n papers, we sampled n papers with replacement 1000 times, estimated α on each sample, and recorded the 95% quantiles of the 1000 resulting estimates.

As well as calculating α for all authors, we calculated α for first or last authors only. α was again defined as $p - q$, but this time p was estimated as the average proportion of male co-authors on papers with a male first (or last) author, and q was estimated as the average proportion of male co-authors on papers with female first (or last) authors. We did not calculate α for other authorship positions (e.g. second or third authors) because this would necessitate reducing the dataset to papers with a sufficiently long authorship list, complicating comparison with other authorship positions that were calculated using a different sample.

Our test assumes that the expected value of α is zero if authors randomly assort, but for small datasets this assumption is not always true (as pointed out by Carl T. Bergstrom in a blog post, http://www.eigenfactor.org/gender/assortativity/note_to_eisen.rtf). To borrow Prof. Bergstrom’s example, consider a small research specialty comprising just two men and two women researchers, who have together produced six two-author papers: one paper in each of the six possible two-author combinations. For these six papers, $\alpha = -\frac{1}{3}$, even though same- and opposite-gendered coauthors were selected in equal proportion to their frequency in the pool of possible collaborators. To control for the fact that the null expectation for α is not necessarily zero (particularly for very small datasets), we devised an adjusted version of the coefficient of homophily, which we term α' . Every time we calculated α for a set of papers, we also determined the expected value of α under the null hypothesis that authors assort randomly with respect to gender. This was accomplished by randomly permuting authors across papers 1000 times, recalculating α , and taking the median. We then calculated α' by subtracting the null expectation for α from the observed value. We also used the null-simulated α values to calculate a two-tailed p-value for the observed value of α ; the p-value was defined as the proportion of null simulations for which $|\alpha_{null}| > |\alpha_{obs}|$. We

applied false discovery rate correction to each set of p-values to account for multiple testing following Benjamini and Hochberg (1995).

As expected, α' was usually almost identical to α (Figure S1), but α was downwardly biased relative to α' for small datasets (Figure S2). Additionally, the correlation between α' and sample size was negligible ($R^2 < 0.01$), suggesting that our calculation of α' effectively removed the dependence of α on sample size. We therefore use the adjusted statistic α' in all analyses.

Minimising the Wahlund effect: discipline and time period

As discussed in the Introduction and shown in Figure 1, the Wahlund effect can give the appearance of gender homophily (reflected in our study as $\alpha' > 0$) whenever one lumps together different ‘subpopulations’ of academic papers that differ in their author gender ratios.

To minimise bias in α' due to the Wahlund effect, we restricted each set of papers to a single research specialty to the greatest extent allowed by our data. Specifically, we only calculated α' for individual journals, since papers from the same journal typically focus on one or a few closely related topics. Although some journals, e.g. *PLoS ONE*, publish research from diverse disciplines with very different author gender ratios (Holman et al. 2018), calculating α' for these highly multidisciplinary journals is still useful as a contrast. The difference in α' between highly multidisciplinary and more specialised journals, e.g. *PLoS ONE* versus *PLoS Computational Biology*, gives a rough estimate of the extent to which multidisciplinary can inflate α' .

As well as varying between disciplines, the gender ratio of authors has changed markedly over time (Holman et al. 2018). Because the gender ratio was more male-biased in the past, α' would be inflated if we calculated it for a sample of papers published over a long time frame. To minimise this effect, we only sampled papers from two one-year periods (namely 2005-6 and 2015-16). The median change per year in % (fe)male authors across journals is $< 0.5\%$ (Holman et al. 2018), and so restricting our dataset to a single year should prevent temporal changes in gender ratio from noticeably inflating our estimates of α' .

Minimising the Wahlund effect: author country of affiliation

A Wahlund effect could arise even if one calculates α' for a single discipline and time period, because of variation in the gender ratio of researchers from different countries. For example, Holman et al. (2018) showed that PubMed-indexed authors based in Serbia are more than twice as likely to be women as are authors based in Japan. Therefore, a dataset containing a mix of papers from teams of authors based in these two countries would contain an excess of same-sex coauthorships, even if collaboration were random with respect to gender within each country.

To address this issue, we also analysed every combination of journal and author country of affiliation for which we had enough data (i.e. 50 or more papers published in 2015-16). For simplicity, we restricted the dataset to only include papers for which Holman et al. (2018) had identified the country of affiliation for all authors on the paper, and all authors shared the same country of affiliation. Restricting the dataset in this fashion produced enough data to measure α' for 325 combinations of journal and country (median: 70 papers and 273 authors per combination).

Calculating standardised journal impact factor

We obtained the 3-year impact factor for each journal from Clarivate Analytics. To account for large differences in impact factor between disciplines, we took the residuals from a model with Log_{10} impact factor as the response and the research discipline of the journal as a random effect. Thus, journals with a positive standardised impact factor have a higher mean number of citations than the average for journals in their discipline. We then used Spearman rank correlation to test whether our estimates of gender homophily covaried with journal impact factor.

Statistical analysis

Previous authors (e.g. Bonham and Stefan (2017)) have hypothesised that senior scientists preferentially recruit staff and students of the same gender, and/or that junior researchers preferentially select same-gendered mentors. In the majority of disciplines, authorship conventions mean that the first-listed author is often an early-career researcher, while the author listed last is more likely to be a senior researcher leading a research team (Wren et al. 2007). Assuming that senior researchers are the main drivers of homophily and that there are enough papers with three or more authors, we predict that the last author's gender will be the strongest predictor of the remaining authors' genders (i.e. the gender of the last author will be more salient than that of the first author, or any other authorship position). This is because the first author's gender would simply be an imperfect correlate of the true causal effect, while the last author's gender would be the causal effect itself.

To test whether α' for last authors tends to be higher than α' for first authors for any given dataset, we used a linear mixed model implemented in the `lme4` and `lmerTest` packages for R, with *authorship position* (first or last) as a fixed factor, and *journal* and *research discipline* as crossed random effects. The response variable was α' , and we weighted each observation by the inverse of the standard error from our estimate of α' , meaning that more accurate measurements of α' had more influence on the results. We used a similar model to test for a difference in α' between the 2005-6 and the 2015-16 datasets, with two differences: we fit year range as a two-level fixed factor (instead of authorship position), and we used α' estimated for all authors (not first/last authors) as the response variable.

The relationship between the gender ratio of authors publishing in a journal and its α' value appeared nonlinear (see Results). We therefore fit a generalised additive model with thin

plate regression spline smoothing, implemented using the `mgcv` package for R.

Theoretical expectations for α when there is a gender gap between career stages

In many STEMM subjects, the gender ratio is more skewed among established researchers relative to early-career researchers (Shaw and Stanton 2012; Holman et al. 2018). We hypothesised that this skew could potentially create Wahlund effects and ‘reverse’ Wahlund effects. For example, imagine that the majority of collaborations are between students and professors, and that the gender ratio is skewed in opposite directions at each career stage: we will then see an excess of mixed-gender coauthorships (heterophily, $\alpha < 0$), even if gender has no causal effect on the selection of coauthors. Similarly, a hypothetical field in which students work only with students, and professors with professors, will have apparent gender homophily ($\alpha > 0$).

Because we can think of no tractable way to control for this issue using our dataset (which contains no information on career stage), we instead decided to derive the theoretical expectations for α when there is a difference in gender ratio across career stages. For simplicity, we assume there are only two career stages, though the results are likely to be general. Under the null model that gender has no causal effect on collaboration, we calculated α for various combinations of the four free parameters: the gender ratios for early- and late-career researchers, and the relative frequency of collaborations between early-early, early-late, and late-late collaborations. We then used the theoretical expectations for α to properly qualify our main conclusions (see Results). The R code used to derive the theoretical expectations can be found in the Online Supplementary Material.

Data availability and reproducibility

The Online Supplementary Material is an HTML document prepared with R Markdown, which contains R scripts used to produce all data, figures and tables. The input data from Holman et al. (2018) is archived at <https://osf.io/bt9ya/>.

Results

Gender homophily by discipline, time period, and authorship position

Figure 2 shows the distribution of α' estimates in 2015-2016 across all journals for which we recovered sufficient data, when α' was calculated for all authors, first authors only, or last authors only. The great majority of journals had $\alpha' > 0$, and for many of these the corrected two-tailed p-values suggested that α' was significantly greater than zero (1469/2077 journals

were significant in 2015-16, and 404/1192 in 2005-6). Only 2/2077 journals had statistically significantly heterophily (i.e. $\alpha' < 0$) in 2015-16, and 1/1192 in 2005-6. The remaining 606 or 787 journals (in 2015 and 2005 respectively) had a value of α' not significantly different from zero, such that we could not reject the null hypothesis of random assortment with respect to gender.

α' was significantly higher in the sample from 2015-16 relative to 2005-6, but the difference in means was small (Figure S3; Effect of the fixed factor ‘Time period’ in a linear mixed model of the data for all author positions: Cohen’s $d = 0.09 \pm 0.04$, $t_{948} = 2.51$, $p = 0.012$).

When comparing pairs of α' values estimated for the first and last authors for the same journals, we found that α' tended to be higher for first authors than for last authors (Figure S4; Effect of the fixed factor ‘Authorship position’ in a linear mixed model: Cohen’s $d = 0.07 \pm 0.02$, $t_{1988} = 4.48$, $p < 0.0001$). This suggests that the gender of the first author was a slightly stronger predictor of the remaining authors’ genders than the gender of the last author, i.e. the opposite of our prediction based on the hypothesis that senior scientists are causally responsible for homophily.

Possible differences in the strength of homophily between disciplines

Figure 2 illustrates the variance in journal homophily values (α') across scientific disciplines. All disciplines had a positive average α' , although homophily appeared somewhat stronger in some disciplines than others (e.g. mean α' was 0.12 ± 0.02 for Urology journals, and 0.03 ± 0.01 for Veterinary Medicine journals; Figure 2, Table S3). However, there was little evidence for strong differences in α' between disciplines: the random factor ‘Discipline’ explained at most 1% of the variance in α' in the two linear mixed models described in the previous section (see Figure 2 and mixed models in Online Supplementary Material). This implies that the processes causing positive α' are similarly strong in all the disciplines we examined.

There was no indication that journals publishing on a wide range of topics have higher α' values than more specialised journals, due to the Wahlund effect. For example, the journal category ‘Multidisciplinary’ - which includes journals like *PLoS ONE*, *Nature*, *Science*, and *PNAS* - did not have notably elevated α' (Figure 2). This result suggests that our estimates of homophily, and estimates from earlier studies, are not notably inflated by the presence of disparate research topics (with variable author gender ratios) being published within individual journals.

Relationship between gender homophily and gender ratio

We next tested whether researchers are more or less likely to seek out same-gendered colleagues in strongly gender-biased disciplines (e.g. Surgery or Nursing), relative to disciplines with a comparatively gender-balanced workforce (e.g. Psychiatry). We found a positive, non-linear relationship between the overall gender ratio of all authors publishing in a particular journal

(as estimated by Holman et al. 2018), and the estimated value of α' for all authors and for first authors (Figure 3). Journals with a balanced or female-biased author gender ratio tended to have higher α' than journals with a male-biased author gender ratio (GAM smooth terms $p < 0.001$, see Online Supplementary Material). The relationship was not statistically significant when α' was calculated for last authors (GAM, $p = 0.142$), though the trend appeared similar (Figure 3).

Relationship between journal impact factor and gender homophily

We observed a noisy but statistically significant linear relationship between discipline-standardised journal impact factor and α' , such that journals with a high impact factor for their discipline had weaker gender homophily than did journals with a low impact factor for their discipline (Figure 4; linear regression: $R^2 = 0.043$, $t_{1415} = -8.0$, $p < 0.0001$).

Analysis accounting for differences in author gender ratio between countries

When we restricted the analysis to only include authors with affiliations from a single country, we found statistically significant homophily for 72 of the 325 journal-country combinations tested (64 unique journals and 18 unique countries), and no significant evidence of heterophily (Figures S5-S6). Additionally, the values of α' calculated for each journal-country combination were mostly very similar to the α' values calculated for the journal as a whole (i.e. when pooling papers from different countries); the average difference in α' was 0.002 (Figure S7). These results suggest that our findings of widespread homophily in the main analysis cannot solely be driven by a Wahlund effect resulting from gender differences between countries.

Theoretical expectations for α when there is a gender gap between career stages

As shown in FIGURE, we confirmed that α is expected to be non-zero, even if collaborators are selected in a gender-blind fashion, if there is a gender gap between career stages. The deviation of α from zero depends on the relative frequencies of collaboration within and between career stages. When $>50\%$ of collaborations were between early and established researchers, we observed gender heterophily ($\alpha < 0$). Conversely, when $>50\%$ of collaborations occurred within career stages, we observed gender homophily ($\alpha > 0$). In a few parameter spaces (shown in red; FIGURE), α was quite high, and overlapped with the values that we estimated (Figure 2).

FIGURE suggests that our main conclusions are likely to be robust to this career stage issue. If A) the gender ratio is highly skewed across career stages (e.g. 50% vs 5% women among early- vs late-career researchers), and B) collaborations between early and established researchers are very rare (e.g. 1% of the total), then α can approach the levels shown in

Figure 2 even if collaborators are selected randomly with respect to gender. The first of these conditions can be rejected for the majority of research fields (Shaw and Stanton 2012; Holman et al. 2018), and the second seems improbable because it is very common for early-career researchers to co-publish with an established mentor. However, one can get $\alpha > 0$ for plausible combinations of parameters (e.g. a moderate gender gap coupled with a moderate excess of within career stage collaboration) will

Additionally, if there is a large gender gap between career stages and collaborations between early and established researchers are commonplace, then α is expected be less than zero if collaborator choice is random with respect to gender. For disciplines where these two conditions are met, our results are likely to under-estimate the extent to which researchers preferentially select same-gendered collaborators.

Discussion

We found evidence that researchers publish with same-gendered coauthors more often than expected under random assortment, even after implementing stringent controls for ‘spurious’ homophily resulting from Wahlund effects (Figure 1). Our data therefore reaffirm and refine the results of earlier studies finding evidence of gender homophily (Ferber and Michelle 1980; McDowell and Smith 1992; Bentley and Adamson 2003; Crow and Smykla 2015; Ghiasi et al. 2015; Araújo and Elsa 2017a; Fahmy and Jacob TN 2017; Jadidi et al. 2017; Teele and Kathleen 2017; Zettler et al. 2017). The excess of same-gender coauthorships was quite strong: many journals had $\alpha' > 0.1$, indicating that the gender ratio of the average man’s coauthors is skewed towards men by $>10\%$, relative to that of the average woman. Few journals had α' values below zero, and almost no journals showed statistically significant gender heterophily after controlling for multiple testing. The results therefore suggest that it is comparatively rare for researchers to preferentially select opposite-gendered co-authors.

An important limitation of our study (and all other similar studies) is that we cannot reliably ascertain what caused the excess of same-gender coauthorships. As well as conscious or unconscious choice by researchers, there could be uncontrolled-for Wahlund effects. We suspect the contribution of these to be minor, since we found positive α' after controlling for three obvious sources of Wahlund effect, but it is not possible to be sure.

Some disciplines exhibit especially skewed gender ratios; e.g. most authors in physics and computer science are men, while most authors in nursing are women (Holman et al. 2018). We hypothesised that these gender-imbalanced disciplines might show the strongest gender homophily, e.g. because one needs to exercise stronger choice (with respect to gender) if one enjoys working with same-gendered collaborators, if one’s field has a large gender gap. By contrast, researchers in fields without a gender gap will have many same-gender collaborators just by collaborating randomly with respect to gender. Contrary to this hypothesis, we found no evidence that gender homophily is restricted to particular disciplines: α' was similarly high across the board Figure 2. Moreover, α' was *lower* for journals with a male-biased author gender ratio relative to those with an even gender ratio, suggesting that women are *less* likely to preferentially seek out women colleagues in male-biased research disciplines.

Interestingly though, α' was highest for journals with a female-biased author gender ratio. One interpretation of this result is that men are more likely to preferentially select male collaborators in fields where men are a minority, relative to the homophily displayed by women in fields where women are the minority. However, this latter result is only tentatively supported by our data, since there are so few journals on PubMed with mostly-female authors Figure 3.

We also found that gender homophily was marginally stronger in 2015-2016, relative to 2005-2006. This suggests that recent increases in the number of women working in STEMM, as well as recent efforts to recruit, retain, and celebrate women in STEMM, have co-occurred with a rising frequency of same-gender collaborations. Although this trend might reflect a change in the gender preferences of researchers seeking collaborators, there are other (probably more likely) explanations that could explain this result. Specifically, we speculate that this trend results from the increasing number of women working in senior positions in STEMM over the past decade (e.g. ???, ???; Bendels and Bauer 2018). Because many co-authorships involve a junior and a senior researcher (e.g. a student and professor), and the gender ratio is typically more male-biased among senior staff than junior staff (Shaw and Stanton 2012; Holman et al. 2018), there will be an excess of opposite-gender collaborations relative to the expectation when there is no difference in gender ratio across career stages. As the gender ratio equalises across career stages, this effect will weaken, causing α' to rise.

We found that journals with a high impact factor (relative to other journals in the same research discipline) tended to have weaker gender homophily than did low-impact journals Figure 4. If one accepts the contentious claim that papers published in high-impact journals tend to be of higher quality than those in low-impact journals (e.g. Garfield 2006), then this result provides non-experimental support for the hypothesis that mixed-gender teams produce better research than single-gender teams (Campbell et al. 2013).

Why does gender homophily exist in science? Collaboration often leads to co-authorship, publications, citations and additional professional recognition, therefore first authors should always be considering collaborators that are most likely to enhance their productivity and in the long term also their academic success, rather than pick co-authors according to their gender. First of all, it is likely that decades ago, the probability to meet a female colleague working on the same area of expertise was slimmer than now. Even though the number of women in STEMM is increasing, i.e. it is not likely to be an obstacle to collaboration anymore; we cannot forgo that female representation in science is still not equal to that of males. Second, the most basic source of homophily is space, scientists are more likely to collaborate with colleagues closer to them in geographic location (McPherson et al. (2001)). In the case of women, personal considerations (e.g. family commitments) represent the principal restrictions on their international mobility. As a result women are less likely to originate collaborations with foreign colleagues [Lemoine (1992); Lewison (2001); @ Webster_2001; @ Lariviere_2011]. Lastly, men and women think differently on average (REF) and are more likely to initiate collaborations based on similarity of thoughts to progress their scientific output (REF).

Academic publishing is one of the most (if not the most) important tool for a researcher to display their work and is frequently used as an indicator of success for being promoted

and hired as a faculty member. Our finding that researchers are more likely to publish with same-gendered co-authors implies that co-authorship listing is not a random process, but instead creates additional gender imbalance. Homophily could make it harder for women to find collaborators in disciplines where women are in the minority (i.e. almost all STEMM fields; Holman et al. 2018). Because women make up for as little as 30% of the STEMM scientist community (Holman et al. 2018), they are less likely to be picked as coauthors, and, as a result, gender homophily creates further gender imbalance and disadvantages for women. Men tend to publish more in high impact journals as first author (West et al. 2013), and generate more citations than papers lead by first author women (Long 1992; Larivière et al. 2013). As a consequence, gender homophily is also likely to contribute to lower publication rates for women (McDowell and Smith 1992).

Although the proportion of women in science has significantly increased over the last decades, women still tend to leave their academic careers behind considerably more often than their male counterparts (Dèbarre et al. 2018). Lack of scientific recognition (Lincoln et al. 2012), lack of research funding (Bozeman and Elizabeth 2004), lack of invitation to speak at scientific events (Isbell et al. 2012; Schroeder 2013; Klein et al. 2017), discrimination during hiring (Reuben et al. 2014; C A et al. 2017) and discrimination when writing a recommendation letter (Trix and Carolyn 2003; Schmader et al. 2007), are only some of the small disadvantages adding up to drive women out of science. Whether their decision to leave academia is deliberate or not, it will negatively impact science overall, as mentoring, networking, and supporting younger women scientists are especially important for women in academia.

Altogether, our findings suggest that researchers preferably collaborate with same-gendered colleagues in STEMM research. Despite using a more stringent analysis method (e.g. Wahlund effects) as well as the largest dataset to date, our results were in accord with longstanding and recent research, while adding new details, reasoning and insight for the current situation. Gender homophily in science not only reinforces the less favorable status of women in science, but also creates long term problems as described above. It is paramount to explore the causes and implement measures to readdress the gender disparity. We advocate for the introduction and implementation of gender policies in order to support opposite sex collaboration, to give men and women a chance to collaborate across gender, fields, and to promote scientific and innovative excellence.

Acknowledgements

We are grateful to XXXX. CM was supported by the Academy of Finland (284666 to the Centre of Excellence in Biological Interactions).

References

- Abramo, G., D. Ciriaco Andrea, and D. C. Flavia. 2009. Research collaboration and productivity: is there correlation?. *Higher Education* 57:155–171.
- Abramo, G., D. Ciriaco Andrea, and M. Gianluca. 2013. Gender differences in research collaboration. *Journal of Informetrics* 7:811–822.
- Araújo, T., and F. Elsa. 2017*a*. The specific shapes of gender imbalance in scientific authorships: a network approach. *Journal of Informetrics* 11:88–102.
- . 2017*b*. Big Missing Data: are scientific memes inherited differently from gendered authorship?. arXiv preprint arXiv 1706.05156.
- Badar, K., J. M. Hite, and Y. F. Badir. 2013. Examining the relationship of co-authorship network centrality and gender on academic research performance: The case of chemistry researchers in pakistan. *Scientometrics* 94:755–775.
- Bear, J. B., and W. Anita Williams. 2011. The role of gender in team collaboration and performance. *Interdisciplinary science reviews* 36:46–153.
- Bendels, M. H., and S. Bauer J. 2018. The gender gap in schizophrenia research. *Schizophrenia research* 193:445–446.
- Benjamini, Y., and Y. Hochberg. 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the royal statistical society. Series B* 289–300.
- Bentley, J. T., and R. Adamson. 2003. Gender differences in the careers of academic scientists and engineers: A literature review. *Special Report*.
- Bonham, K. S., and M. I. Stefan. 2017. Women are underrepresented in computational biology: An analysis of the scholarly literature in biology, computer science and computational biology. *PLoS computational biology* 13:e1005134.
- Bozeman, B., and C. Elizabeth. 2004. Scientists’ collaboration strategies: implications for scientific and technical human capital. *Research policy* 33:599–616.
- Bozeman, B., and M. Gaughan. 2011. How do men and women differ in research collaborations? An analysis of the collaborative motives and strategies of academic researchers. *Research policy* 40:1393–1402.
- C A, M. R., D. J F, B. V L, G. M J, and J. Handelsman. 2017. Science faculty’s subtle gender biases favor male students. *Nature immunology* 18:475.
- Campbell, L. G., S. Mehtani, M. E. Dozier, and J. Rinehart. 2013. Gender-heterogeneous working groups produce higher quality science. *PloS one* 8:e79147.
- Cohn, E. G., P. F. David, and I. Amaia. n.d. Most-cited scholars in criminology and criminal justice, 1986-2010. New York, NY : Springer International Publishing.
- Crow, M. S., and J. O. Smykla. 2015. An examination of author characteristics in national

- and regional criminology and criminal justice journals, 2008–2010: Are female scholars changing the nature of publishing in criminology and criminal justice? *American Journal of Criminal Justice* 40:441–455.
- Dèbarre, F., R. N O, and L. V. Ugelvig. 2018. Birds of a feather: Homophily in social networks. *Evolution letters*.
- Elsevier Report. 2017. Gender in the global research landscape. elsevier.com/research-intelligence/resource-library/gender-report.
- Fahmy, C., and Y. Jacob TN. 2017. Gender Inequality and Knowledge Production in Criminology and Criminal Justice. *Journal of Criminal Justice Education* 28:285–305.
- Feldt, B. 1986. The faculty cohort study: School of medicine. Ann Arbor, MI: Office of Affirmative Action.
- Ferber, M. A., and T. Michelle. 1980. Are women economists at a disadvantage in publishing journal articles? *Eastern Economic Journal* 6:1189–193.
- Fuchs, S., V. S. Janina, and A. Jutta. 2001. Gender, science, and scientific organizations in Germany. *Minerva* 39:175–201.
- Garfield, E. 2006. The history and meaning of the journal impact factor. *JAMA* 295:90–93.
- Ghiasi, G., V. Larivière, and S. Cassidy R. 2015. On the compliance of women engineers with a gendered scientific system. *PloS one* 10:e0145931.
- Health, N. I. of. 2008. Sex/gender in the biomedical science workforces.
- Holman, L., D. Stuart Fox, and C. E. Hauser. 2018. The gender gap in science: How long until women are equally represented? *PLoS Biology* 16:e2004956.
- Hong, L., and P. Scott E. 2004. Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *Proceedings of the National Academy of Sciences* 101:16385–16389.
- Hopkins, A. L., J. W. Jawitz, C. McCarty, A. Goldman, and N. B. Basu. 2013. Disparities in publication patterns by gender, race and ethnicity based on a survey of a random sample of authors. *Scientometrics* 96:515–534.
- Hosek, S., A. G. Cox, B. Ghosh-Dastidar, A. Kofner, N. Ramphal, J. Scott, and S. H. Berry. 2005. Gender Differences in Major Federal External Grant Programs. RAND Corporation.
- Isbell, L. A., Y. Truman P, and H. Alexander H. 2012. Stag parties linger: continued gender bias in a female-rich scientific discipline. *PLoS One* 7:e49682.
- Jadidi, M., F. Karimi, H. Lietz, and C. Wagner. 2017. Gender Disparities in Science? Dropout, Productivity, Collaborations and Success of Male and Female Computer Scientists. *Advances in Complex Systems* 1750011.
- Jordan, C. E., C. Stanley J, and V. Carol E. 2008. Do gender differences exist in the publication productivity of accounting faculty?. *Journal of Applied Business Research*

24:77–85.

Klein, R. S., V. R., S. B M, D. B N, L. T E, and B. et a. J R. 2017. Speaking out about gender imbalance in invited speakers improves diversity. *Nature immunology* 18:475.

Knobloch-Westerwick, S., C. J. Glynn, and M. Huge. 2013. Science faculty’s subtle gender biases favor male students. *Science Communication* 35:603–625.

Larivière, V., Y. Gingras, C. R. Sugimoto, and A. Tsou. 2015. Team size matters: Collaboration and scientific impact since 1900. *Journal of the Association for Information Science and Technology* 66:1323–1332.

Larivière, V., C. Ni, Y. Gingras, B. Cronin, and C. R. Sugimoto. 2013. Bibliometrics: global gender disparities in science. *Nature* 504:211–213.

Larivière, V., E. Vignola-Gagné, C. Villeneuve, P. Gélinas, and Y. Gingras. 2011. Sex differences in research funding, productivity and impact: an analysis of Québec university professors. *Scientometrics* 87:483–498.

Lee, S., and B. Barry. 2005. The impact of research collaboration on scientific productivity. *Social studies of science* 35:673–702.

Lemoine, W. 1992. Productivity patterns of men and women scientists in Venezuela. *Scientometrics* 24:281–295.

Lewison, G. 2001. The quantity and quality of female researchers: A bibliometric study of Iceland. *Scientometrics* 52:29–43.

Lincoln, A. E., P. S, K. J B, and L. P S. 2012. The Matilda Effect in science: Awards and prizes in the US, 1990s and 2000s. *Social studies of science* 42:307–320.

Long, J. S. 1990. The origins of sex differences in science. *Social forces* 68:1297–1316.

———. 1992. Measures of sex differences in scientific productivity. *Social Forces* 71:159–178.

Long, J. S., D. A. Paul, and M. Robert. 1993. Rank advancement in academic careers: Sex differences and the effects of productivity. *American Sociological Review* 703–722.

Martin, J. L. 2014. Ten simple rules to achieve conference speaker gender balance. *PLoS computational biology* 10:e1003903.

McDowell, J. M., and J. K. Smith. 1992. The effect of gender-sorting on propensity to coauthor: Implications for academic promotion. *Economic Inquiry* 30:68–82.

McPherson, M., L. Smith-Lovin, and J. M. Cook. 2001. Birds of a feather: Homophily in social networks. *Annual review of sociology* 27:415–444.

Moss-Racusin, C. A., J. F. Dovidio, V. L. Brescoll, M. J. Graham, and J. Handelsman. 2012. Science faculty’s subtle gender biases favor male students. *Proceedings of the National Academy of Sciences* 109:16474–16479.

O’Dorchai, S., C. Meulders Dani, and A. Margherita. 2009. She figures 2009—Statistics and

indicators on gender equality in science. Publications Office of the European Union.

Reskin, B. F. 1978. Scientific productivity, sex, and location in the institution of science. *American Journal of Sociology* 83:1235–1243.

Reuben, E., P. Sapienza, and L. Zingales. 2014. How stereotypes impair women’s careers in science. *Proceedings of the National Academy of Sciences* 111:4403–4408.

Rosenfeld, R. A. 1991. Outcome analysis of academic careers. Review prepared for the Office of Scientific and Engineering Personnel, National Research Council.

Schmader, T., W. Jessica, and W. Vicki H. 2007. A linguistic comparison of letters of recommendation for male and female chemistry and biochemistry job applicants. *Sex Roles* 57:509–514.

Schroeder, J. et al. 2013. Fewer invited talks by women in evolutionary biology symposia. *Journal of Evolutionary Biology* 26:2063–2069.

Shaw, A. K., and D. E. Stanton. 2012. Leaks in the pipeline: separating demographic inertia from ongoing gender differences in academia. *Proceedings of the Royal Society of London B* 272:3736–3741.

Stack, S. 2004. Gender, children and research productivity. *Scientometrics* 45:891–920.

Teele, D. L., and T. Kathleen. 2017. Gender in the journals: Publication patterns in political science. *PS: Political Science & Politics* 50:433–447.

Tower, G., P. Julie, and R. Brenda. 2007. A multidisciplinary study of gender-based research productivity in the world’s best journals. *Journal of Diversity Management* 2:23–32.

Trix, F., and P. and Carolyn. 2003. Exploring the color of glass: Letters of recommendation for female and male medical faculty. *Discourse & Society* 14:191–220.

Trower, C. A., and R. P. Chait. 2002. Faculty Diversity Why women and minorities are underrepresented in the professoriate, and fresh ideas to induce needed reform. *Harvard magazine* 104:33–37.

Umbach, P. D. 2007. Gender equity in the academic labor market: An analysis of academic disciplines. *Research in Higher Education* 48:169–192.

Wahlund, S. 1928. Zusammensetzung von Populationen und Korrelationserscheinungen vom Standpunkt der Vererbungslehre aus betrachtet. *Hereditas* 11:65–106.

Webster, B. M. 2001. Polish women in science: A bibliometric analysis of Polish science and its publications. *Research Evaluation* 10:185–194.

West, J. D., J. Jacquet, M. M. King, S. J. Correll, and C. T. Bergstrom. 2013. The role of gender in scholarly authorship. *PLoS ONE* 8:e66212.

Wren, J. D., K. Z. Kozak, K. R. Johnson, S. J. Deakyne, L. M. Schilling, and R. P. Dellavalle. 2007. The write position: A survey of perceived contributions to papers based on byline

position and number of authors. *EMBO reports* 8:988–991.

Wright, A. L., L. A. Schwindt, T. L. Bassford, V. F. Reyna, P. A. S. Shisslak Catherine M and Germain, and K. L. Reed. 2003. Gender Differences in Academic Advancement: Patterns, Causes, and Potential Solutions in One U.S. College of Medicine. *Social forces* 68:1297–1316.

Wuchty, S., J. Benjamin F, and U. Brian. 2007. The increasing dominance of teams in production of knowledge. *Science* 316:1036–1039.

Wutte, M. 2007. Closing the gender gap. *Nature* 448:NJ101–NJ102.

Zettler, H. R., Stephanie M Cardwell, and C. Jessica M. 2017. The gendering effects of co-authorship in criminology & criminal justice research. *Criminal Justice Studies* 30:30–44.

Zuckerman, H. 1987. Persistence and Change in the Careers of Men and Women Scientists and Engineers. National Academy Press 127–156.

Figures

The Wahlund effect

Illusory preferences for same-gendered collaborators

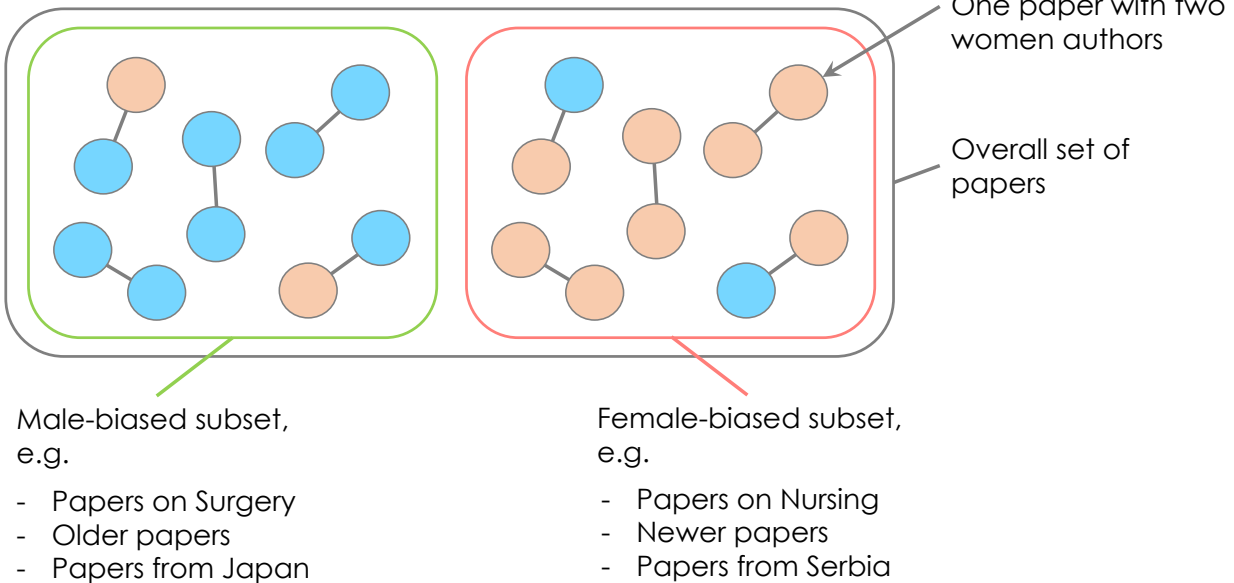


Figure 1: The Wahlund effect can make it appear as if authors prefer to publish with same-gendered colleagues, even if no such preference exists. Here, coloured circles represent male and female authors, and coauthors are linked with lines. Across the whole set of ten papers, there is an apparent excess of same-gender collaborations. Specifically, there are six same-gender papers and only four mixed-gender papers, which is fewer than the $10 \times 2 \times 0.5 \times 0.5 = 5$ mixed-gender papers we would expect under the null hypothesis that authors assort randomly with respect to gender. However, within each subset, there is no evidence that authors prefer to publish with same-gendered individuals. The Wahlund effect will tend to inflate the frequency of same-sex coauthors whenever the data is composed of two or more disconnected subsets of literature with different author gender ratios; these subsets could be research disciplines, older versus newer papers, or papers from authors in different countries.

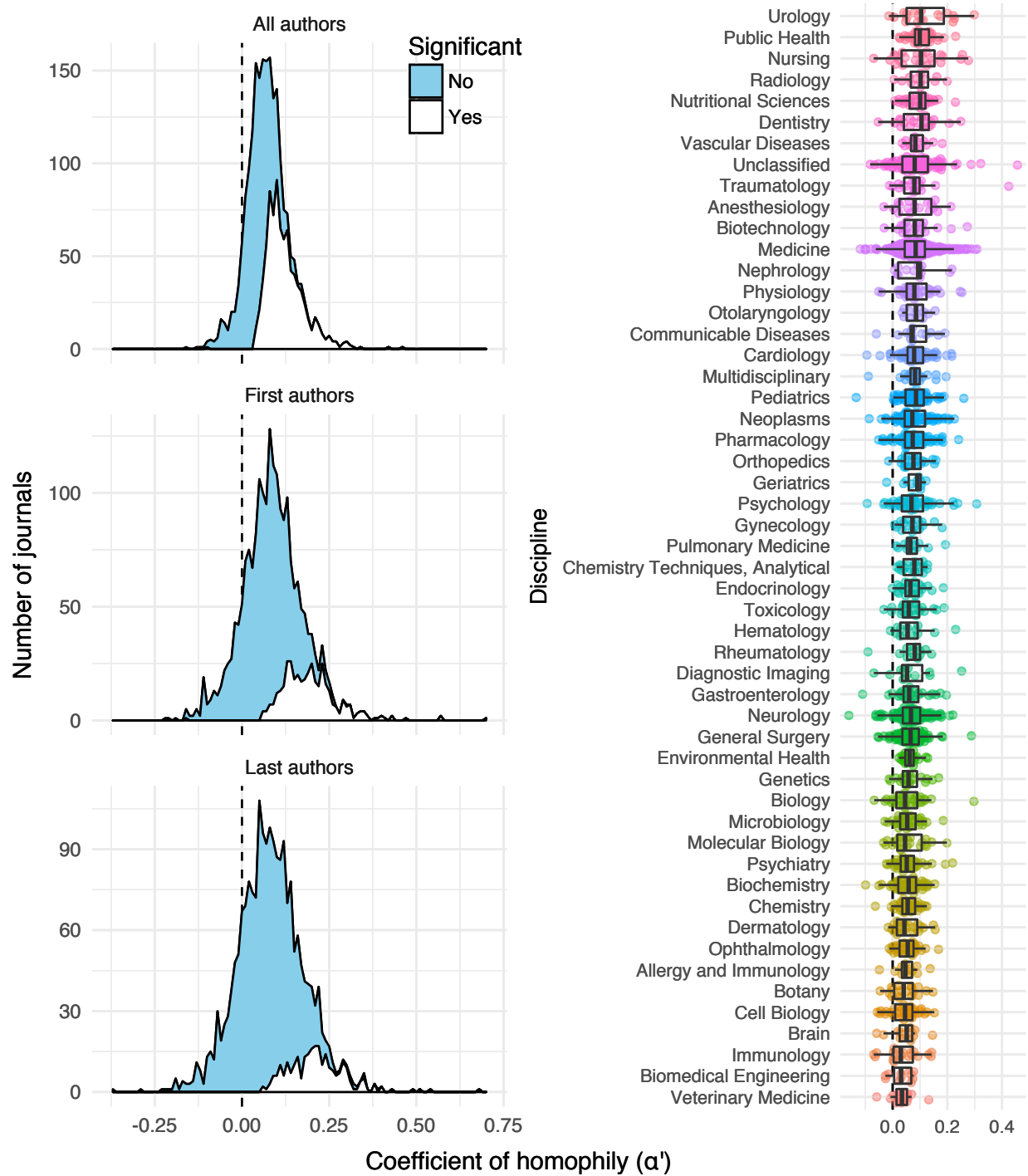


Figure 2: Of the 2077 journals for which we had adequate data in 2015-2016, 830 showed statistically significant evidence of homophily (denoted by $\alpha' > 0$), and 1 showed statistically significant evidence of heterophily ($\alpha' < 0$), after adjusting p-values using Benjamini-Hochberg false discovery rate correction. The white area shows the number of journals for which homophily was significantly stronger than expected under the null hypothesis ($p < 0.05$), while the blue area shows all the remainder. Patterns were similar whether α' was calculated for all authors, for first authors only, or for last authors only.

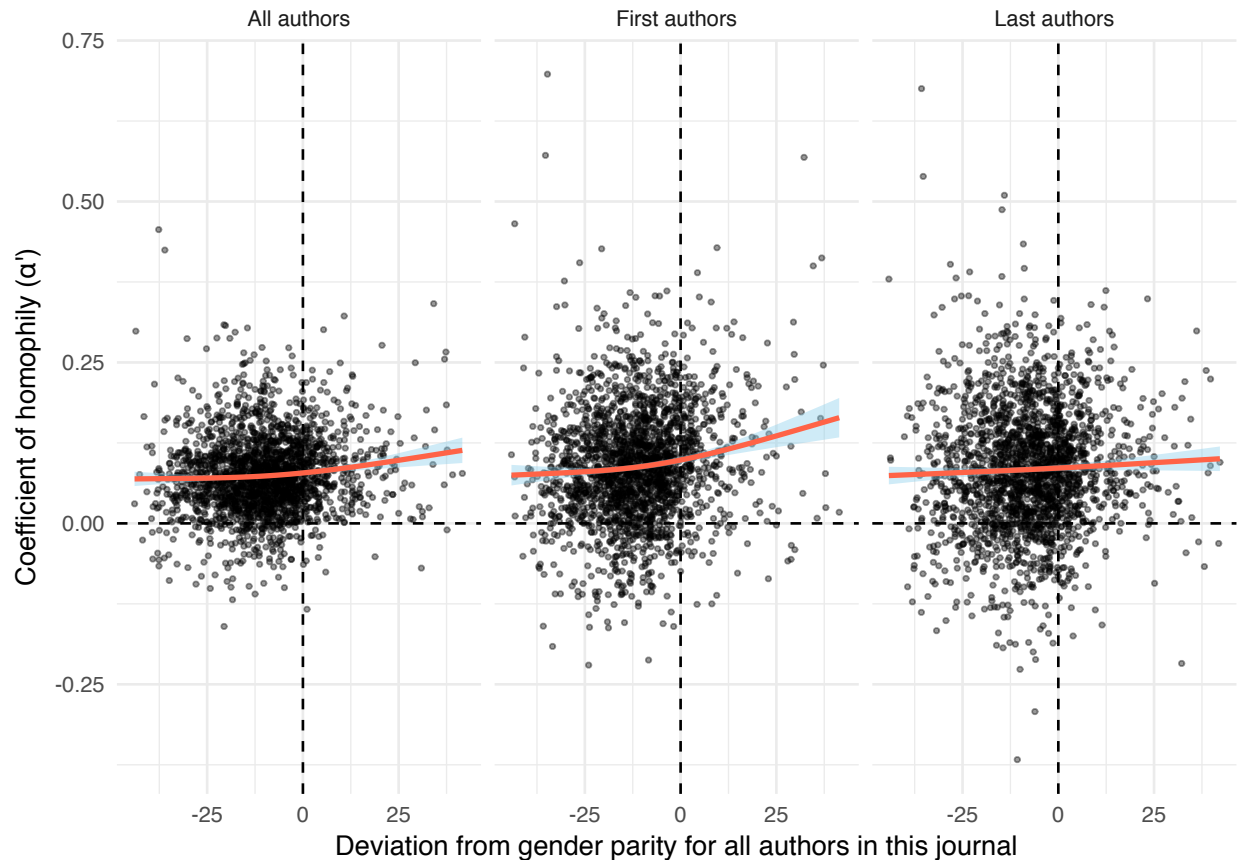


Figure 3: There is a weakly positive, non-linear relationship between the gender ratio of authors publishing in a journal, and the coefficient of homophily (α'). Specifically, journals with 50% women authors or higher tended to have more same-sex coauthorships than did journals with predominantly men authors. This relationship held whether α' was calculated for all authors, first authors only, or last authors only. A negative value on the x-axis denotes an excess of men authors, a positive value denotes an excess of women authors, and zero denotes gender parity. The lines were fitted using generalised additive models with the smoothing parameter k set to 3.

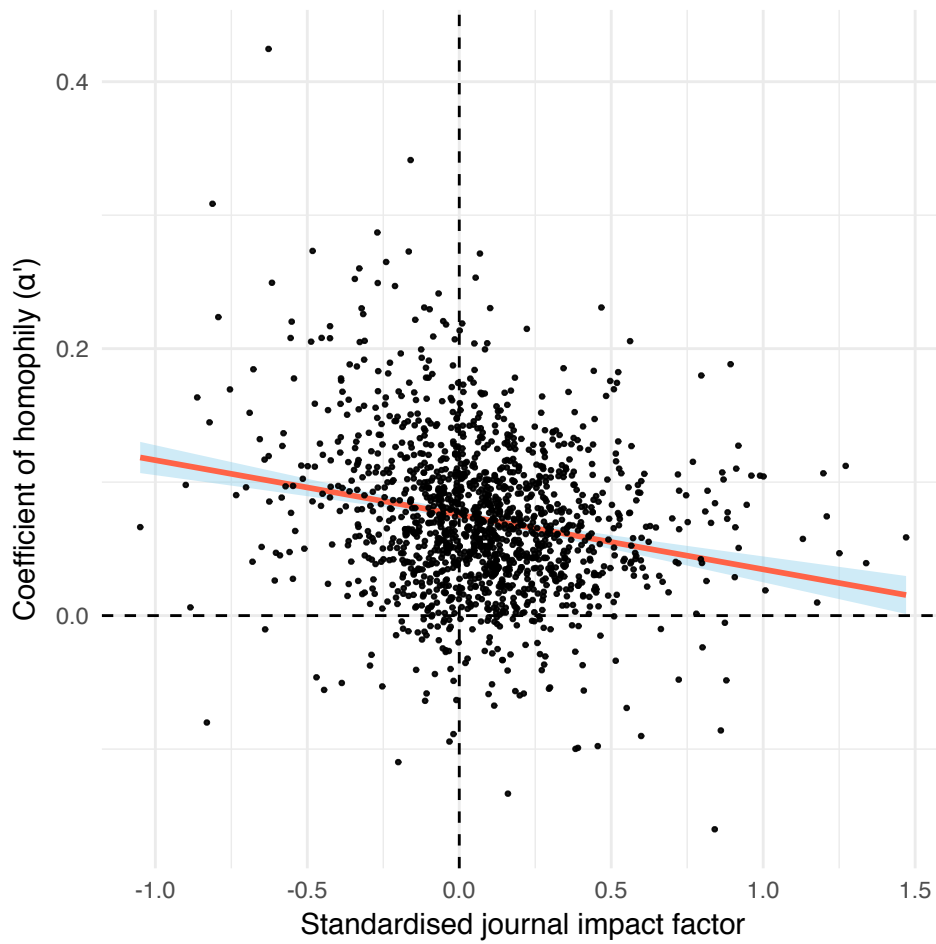


Figure 4: Journal impact factor (expressed relative to the average for the discipline) is negatively correlated with α' . The relationship is noisy ($R^2 = 0.043$), but the results suggest that journals with strong homophily tend to have lower impact factors than journals with weak homophily in the same discipline.

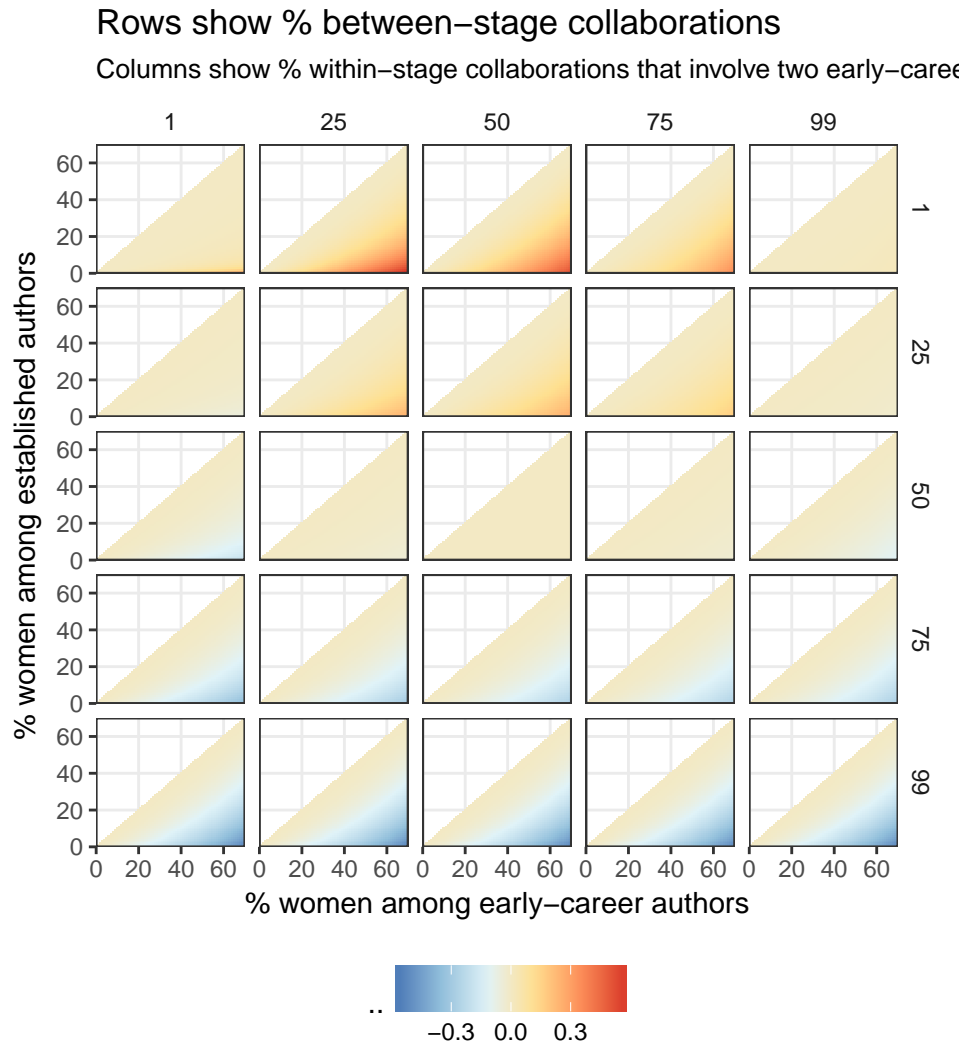


Figure 5: When there is a difference in gender ratio between early-career and established researchers, and collaboration is non-random with respect to career stage, the null expectation for α deviates from zero. An excess of collaborations between career stages gives the appearance of gender heterophily (lower rows, blue areas), while an excess of within-career stage collaborations produced apparent gender homophily (upper rows, red areas). However, the conditions required for strong gender homophily are quite restrictive, making it unlikely that this issue explains all of the homophily observed in Figure 2.