Gender inequities in the online dissemination of scholars' work

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Unbiased science dissemination has the potential to alleviate some of the known gender disparities in academia by exposing female scholars' work to other scientists and the public. And yet, we lack comprehensive understanding of the relationship between gender and science dissemination online. Our large-scale analyses, encompassing half a million scholars, revealed that female scholars' work is mentioned less frequently than male scholars' work in all research areas. When exploring the characteristics associated with online success, we found that the impact of prior work, social capital, and gendered tie formation in coauthorship networks are linked with online success for men, but not for women—even in the areas with the highest female representation. These results suggest that while men's scientific impact and collaboration networks are associated with higher visibility online, there are no universally identifiable facets associated with success for women. Our comprehensive empirical evidence indicates that the gender gap in online science dissemination is coupled with a lack of understanding the characteristics that are linked with female scholars' success, which might hinder efforts to close the gender gap in visibility.

gender inequality | scholarly communication | social networks | STEM | computational social science

Ample research demonstrates gender-based inequities in science, including a lack of visibility for female scientists' work regardless of their career stage (1). It has been shown that women experience gender bias throughout the publishing process. For example, female authors need to meet higher standards to be published (2). They are also impacted more by unprofessional peer reviews (3). Once published, female-authored work has been shown to be less visible in terms of speaking engagements at elite universities (4) and less recognized through citations (5–7), revealing that women's articles are 15 to 30% more likely to be omitted from reference lists than male-authored ones (8). The rise of team-based research imposed additional challenges in terms of unequal credit allocation among team members. Namely, men have been shown to be more likely to benefit from collaborative work (9), while in some areas the coauthorship was found to impact female scholars' tenure applications negatively (10). However, previous research also found that women are disadvantaged if they do not collaborate with men (8, 11), suggesting that women need to navigate a more complex environment to achieve success. The disparities in success persist despite evidence regarding the benefits of gender-diverse scientific teams (12–15) and the costs associated with the lack of diversity, which range from not developing proper medical diagnoses and interventions for women (16) to not ensuring that technological innovations profit everyone equally (17). Yet, closing the gender gap in science has proved to be extremely difficult (18, 19).

Unbiased science dissemination might alleviate some of the known inequities, as it is the crucial first step in exposing scholars' work to other scientists and the public. Science dissemination is happening increasingly through social media (20, 21), a trend further expedited by the COVID-19 pandemic (22). Online platforms offer a promise of broader participation and wider dissemination, especially for underrepresented groups, by bypassing traditional gatekeepers in publishing and conference organizing (23). Gaining visibility for one's work early on is important since it can lead to significant citation benefits through the effect of cumulative advantage (24). Furthermore, both correlational analyses (25, 26) and randomized controlled trials (27) suggest a significant positive association between social media dissemination and traditional scholarly impact.

Another development making the successful dissemination of research more relevant is the increasing quantification of attention received online via so-called altmetrics (hereafter, online success) and its penetration into science evaluation (28) as a research metric (29). Given the importance of the successful sharing of research, scientific communities have been working on developing and popularizing best practices for using social media for science dissemination (30). It is thus crucial that scholars' online success (defined as the number of mentions of their scientific articles online) does not perpetuate well-known disparities in science. Yet, there is indication that much like scientific success offline, the online success of scientists is unlikely to be gender neutral (31). For instance, there is some evidence that scientific communication on social media is disproportionately male dominated (20, 32), which makes women less likely to

Significance

Prior work establishes wide-ranging gender inequities in science. Disparities at the level of earnings, support, and promotion indicate that women's research is not recognized equally to men's. Since an imbalance in visibility might have consequential downstream effects on citations and awards, the study of online success is critical to address the gender gap. Here we show that women are less successful than men in disseminating their research online. We demonstrate that scientific impact, social capital, and gendered tie formation in coauthorship networks are associated with the online success of men across research areas and levels of success, but not of women.

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participate in and benefit from it. Men also blog more (33) and edit Wikipedia at a higher rate (34). Self-promotion is a crucial factor in online success, but women typically avoid it because of the fear of backlash (35). Since online mentions of scientific articles are mainly done by colleagues and other academics, scholarly activity online is likely to be primarily an extension of scientists' offline network. When women try to utilize online platforms for science dissemination, they may thus face similar barriers to those offline. These include the glass ceiling effect (36), induced gender homophily (37), and unintended backlash (38), all of which might make women likely to develop more unique and less generalized success strategies (39, 40).

The question is then, Has online dissemination realized its potential as an equalizer, or have inequalities in formal communication been simply moved to the online environment? Furthermore, are these trends universal or dependent on a scientific field or discipline? To answer these questions, we studied 537,486 scientists from Altmetric (the largest service that tracks online mentions of research articles) who had at least one article shared online in 2012. For these scientists we collected data on publication history and collaboration networks for 5 preceding years using the Open Academic Graph (41). We also used information from the Web of Science (WoS) to classify articles into broad scientific areas based on the references within publications (42) and to extract topics from article titles (43). We inferred each author's gender with a method using the author's first name (44). This gender imputation algorithm handles international names well and yielded 51.6% men, 28.6% women, and 19.8% unknowns among the considered scientists (*Materials and Methods*). Our large-scale analyses and models thus provide a comprehensive examination of the empirical link between the online success of scientists and gender-related characteristics of scientific production. Most importantly, our study covers various broad research domains and points to a critical lack of universal trends in the characteristics that are associated with the online success of female scientists.

Results

We started by examining the gender composition of authors whose work is tracked in Altmetric, i.e., shared on social media sites, in online news, blogs, and other websites. We found that 28.6% of scholars whose articles were mentioned online in 2012 are women. As expected, this percentage varies considerably by broad research area, ranging from 16 to 17% in physics, mathematics, astronomy, and engineering to 47% in psychology (Fig. 1, *Left*). By themselves these numbers do not tell us much, since they do not take into account the number of women who actually published their research that year. Therefore, we compared the above percentages with a simple baseline computed as the proportion of women who had an article recorded in WoS in that same year and research area. We found that the online representation of women is lower than expected from their publication activity across the board, with underrepresentation being most pronounced in chemistry, biological sciences, and geosciences, where it exceeds 7% (Fig. 1, *Middle*). The underrepresentation of female scholars' work online is an enduring trend. Five years later, the online presence of women was higher on average by 5% than in 2012 (*SI Appendix*, Fig. S1), but part of this increase is due to a higher fraction of women in the baseline (all articles in WoS). Although the gap is narrowing, the online presence of women remained lower than expected based on WoS across all broad research areas.

Being mentioned online once in order to be registered in Altmetric is just the lowest threshold of online presence. It represents a relatively low level of online success (although better than not being mentioned at all). We next distinguish authors with different levels of online success by taking into account how much online attention they get. We place researchers based on the total mentions of all articles they authored in 2012 into four "success" categories: top 25%, top 15%, top 5%, and top 1%. Each higher category contains the subset of authors from the lower category. We find that women's underrepresentation typically gets more severe as we focus on a higher success category (Fig. 1, *Right*). Except in astronomy, women are more underrepresented in the top 1% category than in the top 25% category in

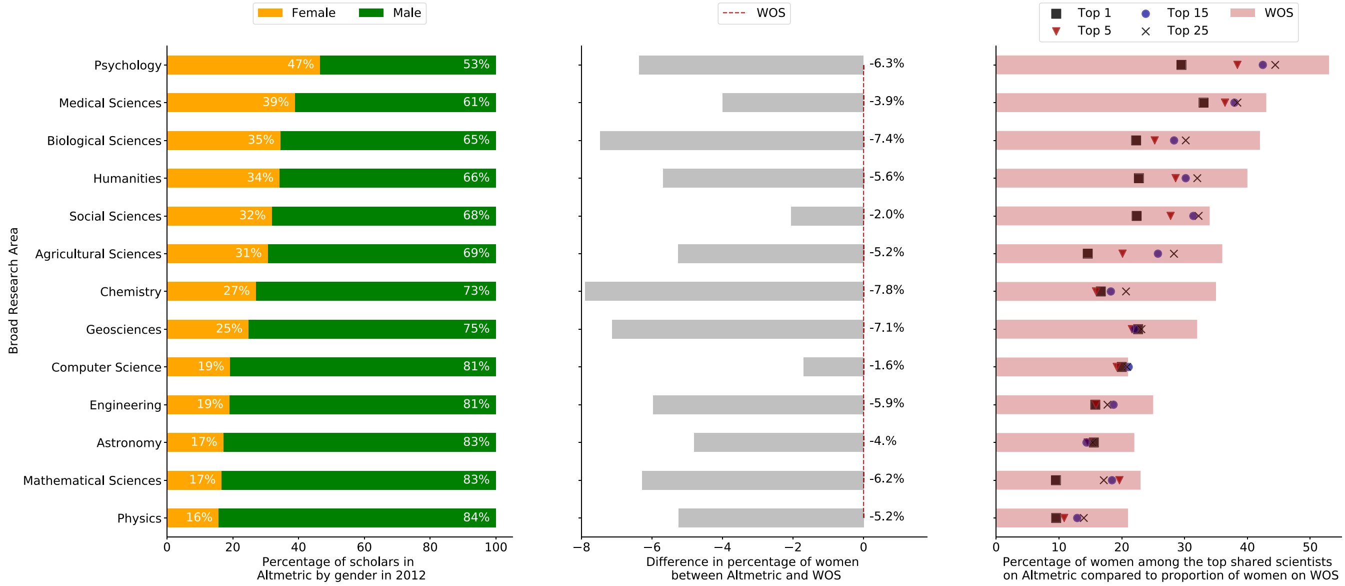

Fig. 1. Online success of female scholars in various broad research areas. (*Left*) Percentage of women among the scholars who had articles mentioned online in 2012. (*Center*) Online representation of female scholars based on Altmetric in comparison with the ratio of women who published research papers in 2012 according to the WoS. (*Right*) Proportion of women in the top 1, 5, 15, and 25% of the scientists with the most mentions online, compared with percentage of women who published according to the WoS. Note that overall our gender imputation algorithm could not unambiguously determine the gender of 19.8% of the scholars.

all areas, although the level of decrease in representation varies from area to area. To understand the statistical significance of this decrease in representation we computed conditional probabilities of being in a certain success category (e.g., top 15%) given presence in a lower success category (e.g., top 25%). We also performed bootstrapped significance tests to account for randomness in the computed conditional probabilities (*Materials and Methods*) and found that in 8 of 13 broad research areas (agricultural sciences, astronomy, and mathematical sciences [Fig. 2], but also chemistry, computer science, humanities, medical sciences, and physics) the lower fraction of women in the top 5% group compared to the top 15% was statistically significant. These research areas also tend to be the ones with lower representation of women in general.

Characteristics Associated with Scientists' Online Success. Research shows that productivity, impact, and the structure of coauthorship networks influence success associated with formal publications (45, 46) and are likely to impact online success as well. For example, indicators of scholars' productivity and impact have been related to the online dissemination of their work (25). Similarly, social capital encompassed by coauthors who could endorse one's work by sharing it online was also found to contribute to scholars' visibility and promotion (47). To systematically explore characteristics that may affect online success, we created four groups of variables based on scholars' prior track record. The first group quantifies scientific impact and includes the following variables: 1) previous productivity defined as the number of articles researchers wrote in the preceding 5 y (5, 48); 2) scientific success measured by the *h* index of scholars in 2012 (49); 3) prestige of the publication venues quantified as the sum of the impact factors of the journals where their articles were published (45, 46); 4) the number of articles published in high-impact journals that have an extensive science dissemination network (50); and 5) number of articles on a hot topic, which is defined as the 20% of most shared topics in a broad research area to account for the link between article topic and received citations (51).

The other three variable groups (social capital, network femaleness, and network maleness) capture features of scholars' weighted collaboration networks constructed using information about coauthorship on all the publications from the 5-y period (2007 to 2012). The first of these variable groups focuses on the reach of social capital and measures 1) scholars' number of collaborators in the previous 5 y (52); 2) the density of their ego network (5, 53) defined as a subnetwork containing scholars, their direct coauthors, and all collaborations among those coauthors; and 3) the average size of coauthor teams on individual articles during this time (48). Since gendered tie formation has been shown to impact success in various domains (5, 54, 55), we include two groups that describe each scholar's collaboration with men and women, respectively. Accordingly, network femaleness variables capture collaboration with women through 1) number of papers in female-majority teams based on the average female ratio in each broad research area; 2) female homophily among coauthors as the ratio of female–female ties; and 3) average tie strength to women, which equals the average number of papers coauthored with women. Similarly, network maleness variables describe the same collaboration patterns with men, i.e., 1) number of papers in male-majority teams, 2) male homophily, and 3) average tie strength to men.

To identify characteristics associated with online success, we performed logistic regression modeling for each broad research area. To reduce the noise in individual variables, the modeling was performed on the principal components of each group of variables (scientific impact, social capital, network femaleness, and network maleness) (*Materials and Methods*). High positive values of the principal component in each group indicate above average scientific impact, a large and sparse ego network, participation in big coauthor teams, and strong, active collaborations with women and men. The indicator of online success we used in the regression models is the presence or absence among the top 25% of scientists based on the number of article shares in Altmetric. The results of the regression analysis for the four variable groups by broad research area are shown in Fig. 3. The explained variance of the models ranges from 0.15 in the social sciences to 0.31 in chemistry (see *SI Appendix*, Table S1 for details about model fit and sample sizes). Alternatively, an Oaxaca–Binder decomposition indicates that 61 to 83% of the overall variance can be explained by these variables, depending on the broad research area (*SI Appendix*, Fig. S3). Overall, we found that all four variable groups are strongly and positively associated with male scholars' online success. For female scholars, the relationship between the same variable groups and online success reverses, weakens, or becomes nonsignificant, suggesting that these characteristics are not linked with women's success like they are with men's.

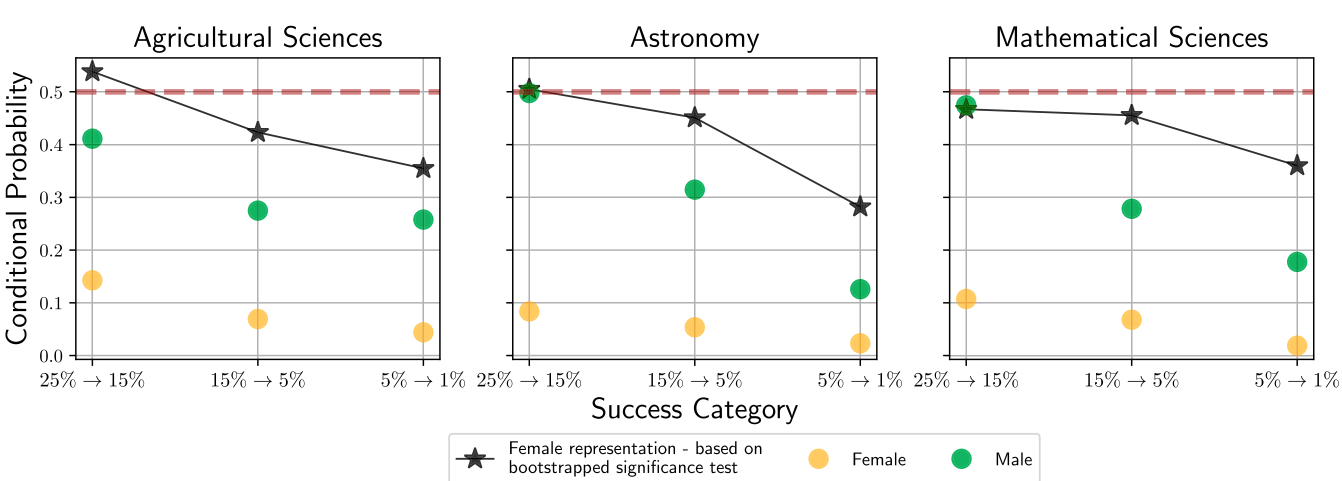

Fig. 2. Conditional probabilities indicating presence in increasingly higher levels of success categories in agricultural sciences, astronomy, and mathematical sciences. The bootstrapped significance test evaluates women's representation in the higher level of success category by comparison with their representation in the lower level of success category. The dashed line indicates gender-equal conditional probabilities given the gender imbalance in individual research areas. Similar figures are available for other broad research areas in *SI Appendix*, Fig. S2.

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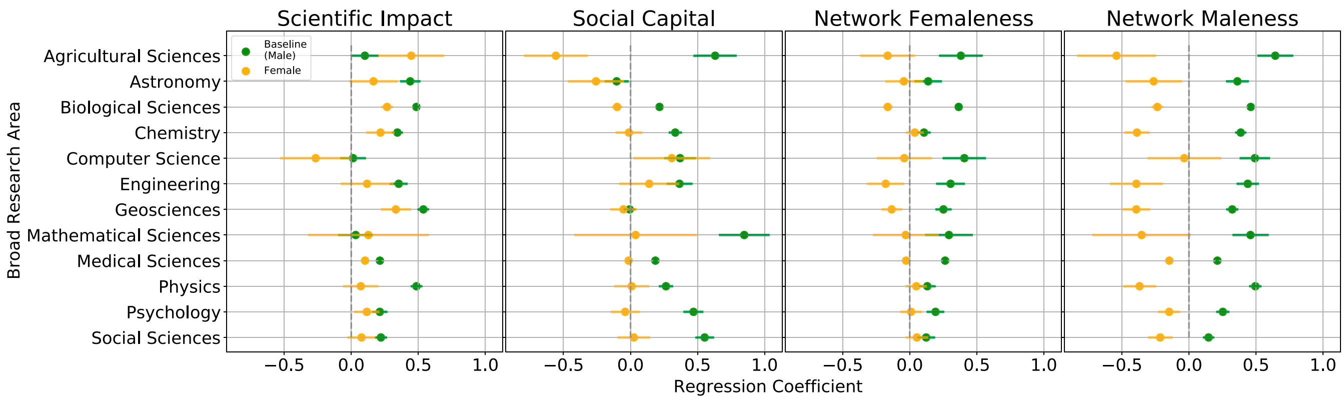

Fig. 3. Coefficients and 95% confidence intervals of the variable groups in predicting the 25% of most successful scientists by broad research area. Green points indicate the baseline prediction (men), while orange points correspond to the prediction controlled for gender (women). *SI Appendix*, Table S1 provides details and a discussion of area-dependent trends.

The less than perfect predictive power of the success facets we examined suggests that there is relatively little overlap between the most successful scholars based on traditional offline measures of success like the h index (49) and the ones based on online success. Furthermore, we expect the overlap to be worse for female scientists. Indeed, we found that a higher overlap between the scientists who are among the top 25% based on both h index and article shares online results in better model accuracy (Spearman's correlation: $\rho = 0.85$, $P = 0.000$), with the best accuracy achieved in chemistry ($R^2 = 0.31$), where the overlap between the offline and online successful scholars is 43%. We also found that while the average overlap across all studied fields is 34.4%, this simple measure is consistently higher for male scientists (on average, 39.8%) than for female ones (on average, 25.3%). The measure we used for offline success (h index) is affected by seniority (56), which suggests that in a number of fields, it is young rather than senior female scientists who are attracting attention online, which might be the result of larger gender disparities in the past. To probe this finding further, we examined the levels of discrepancy between the scientists who are among the top 25% based on their online success and those who are among the top 25% based on their h index for all fields (Fig. 4). We also took into account over/underrepresentation of research areas in Altmetric compared to WoS. A few things stand out. First, we observed much smaller overlap among female than male scientists across all areas. Furthermore, we found equally high discrepancy (over 75%) in both over- and underrepresented areas, with astronomy (the most overrepresented area) and psychology (slightly underrepresented area) having close to 80% discrepancy among the female scientists. Overall, these results suggest that while there are not clearly identifiable facets associated with female success online and while women's work is still being underrepresented on the web, less-established (potentially younger) female scientists are using online platforms for science dissemination, incorporating them as tools in their unique paths to online success.

Discussion

In this paper we analyzed half a million scientists' online success in 13 broad research areas ranging from medical sciences to physics and to the social sciences. We found that online science dissemination is male dominated and female scientists are less likely to belong to the top 25% of the most successful scholars online in all of the studied research areas. Moreover, similar to traditional offline settings, we found a glass ceiling effect in 8 broad research areas where women are less likely to reach the top 15, 5, and 1%. We were able to test how scientific impact, social capital, and gendered tie formation in coauthorship networks interact with authors' gender to determine their success online. We found evidence across research areas that male scholars' online success is linked with all of these characteristics. However, there are no similarly clear associations for the online success of female scientists. Instead, even in broad research areas with better female representation, there is a gender gap with women obtaining less visibility from the same level of scientific impact than their male colleagues. Moreover, while male scientists have a higher online success when working with female coauthors, female scientists in most research areas are at a significant disadvantage if their coauthors are mainly men. We also find that the overlap between who is successful online and whose work has garnered scientific impact offline is lower for women than for men, which suggests that online platforms

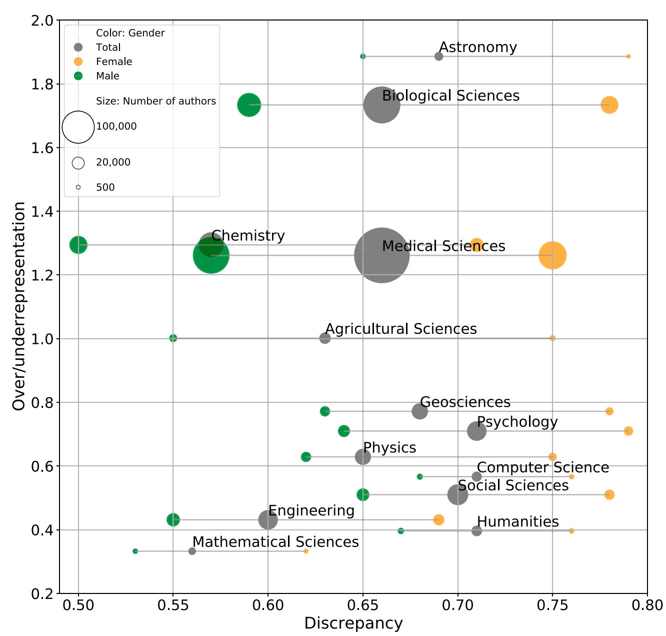

Fig. 4. Discrepancy and over/underrepresentation of broad research areas. Discrepancy is defined as the percentage of scientists who are among the top 25% based on their online success but do not belong to the top 25% according to h index. Discrepancy is shown per research area for the entire sample of scholars (gray circle), only men (green), and only women (yellow). Circle size indicates the number of scholars who had article mentions on Altmetric in each of those three groups. Over/underrepresentation of broad research areas on Altmetric is evaluated in comparison with WoS.

can indeed increase the visibility of female scientists beyond that of those whose success is already well established offline. It is all the more important, then, to continue this line of research to better understand the creative paths to online success for female scholars.

Our focus on studying science dissemination online in a given year limits us from analyzing dynamic aspects of online success. Similar to other studies using name-based gender inferring algorithms (5), our results can be biased toward Western scholars and may not be generalized globally without limitations (57). Furthermore, English language publications and STEM (Science, Technology, Engineering, and Mathematics) fields are overrepresented in our data sources. Our analysis also calls for further scrutiny of the gendered aspect of online success in relation to the multiple and individually less controllable factors that influence the dissemination of a scientific finding online, such as how interesting and understandable the research topic is for the wider scientific community and the public (58), as well as the demographic characteristics (32) and the overall technological savviness (20) of the research community. Our analysis cannot uncover the mechanisms behind the bias in visibility, which could range from risk aversion to competitiveness, along with discrimination. We can only conjecture that female scholars' online success is an extension of well-documented offline disparities.

Notwithstanding these limitations, our study provides evidence that female scientists are less successful online than male ones across all areas of science. This evidence complements studies showing that women continue to systematically receive less credit via citations than men (5–8), are talked about in ways that reflect a perception of less fame and eminence (59), and are still significantly less likely to receive prestigious awards such as the Nobel Prize (60). Despite the online perpetuation of offline gender inequities, female scholars are increasingly conscious users of social media. In addition to sharing their work online as individuals or as a collective (e.g., Women in Data Science), they promote STEM careers for young girls through channels such as women.doing.science on Instagram and 500womenscientists on Twitter and create support networks such as the Academic Mamas* Facebook Group. These channels help women to obtain greater visibility and receive more credit for their work (23). This cultural shift has already sparked remarkable achievements such as creating a push to update academic curriculum to be more inclusive and claiming gender equity in academic departments, panels, and conferences (61–63). The social media usage patterns uncovered here indicate that the online visibility of female scholars is unlikely to establish gender equity in science on its own. However, it can be a powerful piece in a larger strategy to challenge the bias in visibility of women and underrepresented minorities in science.

Materials and Methods

Data. Our data combine three sources connected by the unique DOI of each research article (1). Data from http://www.Altmetric.com contain articles published in 2012 with their mentions in public social media posts, e.g., on Twitter, Facebook, and Reddit; their coverage in online news; and citations on Wikipedia, in policy documents, and on research blogs (2). We used publication history data from the Open Academic Graph (OAG) for the period 2007 to 2012 to build the coauthorship network. Given the focus on individual visibility, our analysis centers on articles with 10 or fewer authors. Beyond information on collaborations, we used this source to quantify scholars' previous productivity and success, such as the number of articles they wrote in the preceding 5 y and their h index in 2012 (3). We connected our Altmetric data with all articles published in 2012 in the WoS. We used WOS data to determine the broad research area of articles (42). We identified 244 unique scientific subfields, such as "clinical neurology," "mechanical engineering," and "nuclear physics." We aggregated our combined Altmetric-OAG-WOS data at the level of individual scholars based on the unique "author id" available in the OAG, by assigning the attributes of an article to all its authors. The combined data contained 241,386 articles by 537,486 scholars. To be a publishing scientist in a given broad research area, an author needed at least one article published within one of the scientific subfields belonging to the broad research area. Therefore a scientist could belong to multiple broad research areas. See *SI Appendix*, Table S2 for descriptive statistics of the resulting dataset.

Gender Imputation. To identify scholars' gender we adopt a commonly used method based on their first names (44, 55). We ran the algorithm developed by Ford et al. (44) on the three data sources. The algorithm uses a conservative heuristic to establish gender, leaving unlabeled 19.78, 37.80, and 22.42% of the scholars on Altmetric, WOS, and OAG, respectively (*SI Appendix*, Table S3). To test the accuracy of gender imputation, we took a random sample of 100 scientists from the Altmetric data and manually checked their gender based on information available about them online. We found that this small sample contained 66% males, 28% females, and 6% scholars of unknown gender. Then, we validated the gender imputation algorithm using the manually confirmed genders as the baseline. The accuracy of the algorithm on the baseline set was $F1_f = 0.87$ and $F1_m = 0.90$. This score reaches 1 when both precision and recall are perfect (*SI Appendix*, Fig. S4). Using Python's standard Gender Guesser package resulted in similar accuracy in imputed genders: $F1_f = 0.86$ and $F1_m = 0.91$.

Presence in Increasingly Selective Success Categories. We conducted a bootstrapped significance test to evaluate women's representation when going to higher levels of online success. To evaluate the resulting conditional probabilities, we took a random sample from the lower success category (e.g., top 25% with both genders included) such that the sample contained the number of scholars who were in the higher level of success category (e.g., top 15%). Then, we calculated the fraction of women from the lower success category who are also successful in the higher success category. We repeated the process 10,000 times and computed the fraction of trials that resulted in a higher female ratio than in the lower success category. If this fraction is lower than 0.5, then women are underrepresented; if it is higher than 0.5, then women are better represented than expected.

Principal Component Analysis. We conducted principal component analysis (PCA) on each variable group separately for each broad research area producing components for scientific impact, social capital, and network maleness and femaleness. We used scipy's PCA.decomposition package with Varimax rotation in Python. In *SI Appendix*, Figs. S5 and S6 show the correlation between individual variables and the resulting factors. *SI Appendix*, Table S4 shows the explained variance of each principal component by broad research area and indicates that all factors retain at least 40% of the variance.

Model Specification and Robustness. To tackle the binary classification problem of whether a scholar is successful online or not, we employ a logistic regression classifier, which is an out-of-the-box supervised learning approach. We run the models for each broad research area separately and we exclude from all models authors with unknown gender. Each of our models contains the factors capturing scientific impact, social capital, network femaleness and maleness, their interactions with gender (i.e., a dummy variable flagging female scholars), and control variables that capture the number of articles published in individual subfields of the broad research areas. To evaluate the robustness of our models, we tested them using 1) a different definition of online success (based on the 5% of the most frequently mentioned scholars, rather than 25%; *SI Appendix*, Table S5); 2) alternative evaluations of model accuracy such as recall, precision, F1 score, accuracy, and Area Under the Curve (*SI Appendix*, Table S6); and 3) gender-balanced samples that contained the same number of men and women in each research area (*SI Appendix*, Tables S7 and S8).

Data Availability. We obtained Altmetric data through the company's free Researcher Data Access Program (https://www.altmetric.com/research-access/). Web of Science data by Clarivate Analytics is available for cost from https://clarivate.com/webofsciencegroup/solutions/web-of-science/. In addition, affiliates of member institutions can access Web of Science data for free through CADRE at https://cadre.iu.edu/about-cadre. The Open Academic Graph dataset is publicly available here: https://www.microsoft.com/en-us/research/project/open-academic-graph/. While we cannot redistribute these data, we are sharing a description about how to access these resources at https://github.com/LINK-NU/PNAS-Online-Dissemination-Gender. On the same link, we also provide aggregate and anonymized data at the level of individual scholars that are required to reproduce our findings and figures.

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