Investigating the division of scientific labor using the Contributor Roles Taxonomy (CRediT)

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Abstract

Contributorship statements were introduced by scholarly journals in the late 1990s to provide more details on the specific contributions made by authors to research papers. After more than a decade of idiosyncratic taxonomies by journals, a partnership between medical journals and standards organisations has led to the establishment, in 2015, of the Contributor Roles Taxonomy (CRediT), which provides a standardized set of 14 research contributions. Using the data from PLOS journals over the 2017-2018 period (N=30,054 papers), this paper analyses how research contributions are divided across research teams, focusing on the association between division of labor and number of authors, and authors' position and specific contributions. It also assesses whether some contributions are more likely to be performed in conjunction with others and examines how the new taxonomy provides greater insight into the gendered nature of labor division. The paper concludes with a discussion of results with respect to current issues in research evaluation, science policy, and responsible research practices.

Keywords

Authorship • Contributorship • CRediT • Public Library of Science • Gender

Introduction

Scientific authorship is regularly considered as the primary currency in academia, whether for hiring, promotions or priority disputes (Biagioli and Galison, 2003; Cronin, 2001; Pontille, 2004). Yet, from the 1950s onwards, issues have been progressively raised about the use of authorship for attributing scientific capital (Bourdieu, 2001). These issues can be grouped into three categories. The first one relates to the increasing number of authors per article (Zuckerman, 1968; Larivière et al., 2015). In some domains such as clinical research, genomics, and high-energy physics—where articles often bear several hundreds or thousands of names in the byline—identifying respective contributions and, thus, assessing individual researchers' contributions, is increasingly difficult. Second, with the rise of multidisciplinary projects, the meanings attributed to authorship—and to name ordering—have multiplied, with unintended consequences for authorship (Paul-Hus, Mongeon, Sainte-Marie and Larivière, 2017; Smith et al, 2020a, Smith et al., 2020b). The frictions of conventions have sown discord among the participants in research projects (Wilcox, 1998) and greater confusion has also prevailed among gatekeepers (Bhandari et al., 2003). Third, scientific research has regularly—and some may argue increasingly (Azoulay Furman, Krieger, and Murray, 2014)—been shaken by cases of fraud. In some alleged cases, all authors on a work under investigation have asked journals to remove their names from publications. Such a systematic denial of responsibility has gone to the point that certain articles have found themselves "orphaned" (Rennie and Flanagin, 1994).

Considering these different aspects as undermining factors in the fair attribution of scientific contributions, researchers, journal editors, research administrators, and members of funding bodies have been looking for alternative ways to assign authorship. This issue has been of particular concern in the biomedical sciences, given the immediate public concerns that occur when research lacks transparency. Over the last few decades, discussions and debates have taken place in major journals, several workshops have been organized, and an "authorship task force" group was formed to imagine better ways of attributing credit for scholarly publications (Davidoff, 2000). This collective exploration has resulted in at least two concomitant phenomena: the development of more precise vocabulary for authorship malpractice and the development of new authorship attribution devices.

A new vocabulary has progressively emerged to characterize controversial authorship practices (Sismondo, 2009; Pontille, 2016). Omission of a researcher who contributed significantly to the project—ghost authorship—is one of the most frequent of transgressions and also one of the most difficult to count (given that omission is often of junior scholars or more technical contributors who may lack capital in science). This is particularly problematic in some disciplines; for example, a survey of biomedicine suggests that about one-fifth of all papers exhibit ghost authorship (Wislar, 2011). Ghost authorship is also fairly common in industry-initiated trials, where most ghost authors are statisticians (Gøtzsche et al., 2007). This may be less malicious than other forms of authorship misconduct and more of a reflection of differing forms of capital exchange between industry and academe. However, the more pernicious relative of ghost authorship is ghost management of research by pharmaceutical companies (Sismondon and Doucet, 2010). These practices demonstrate the flip side of authorship: where ghost authorship calls attention to the lack of rewards for the author, ghost management highlights the issues that arise when there is no transparency in accountability. Honorary authorship falls on the other side of the coin: providing reward where there was no labor. Two forms of this have been identified: guest and gift authorship. Guest authorship designates already recognized names that stand as a sign of quality and potentially increase the chances for the article to be published (Haeussler and Sauermann, 2013). Gift authorship sets up a principle of reciprocal exchange between colleagues, resulting in the inclusion of people as authors regardless of their actual contribution (Smith, 1994; Street et al., 2010). Levels of honorary authorship on scholarly papers have been reported between 20% to 40% (Flanagin, et al., 1998; Hardjosantosao, et al., 2020; Mowatt, et al., 2002).

To mitigate instances of misconduct, new attribution devices have been proposed. For instance, Richard Horton, Editor-in-Chief of the *Lancet,* suggested that the relationship between journal editors and researchers be conceived as a legal contract, each of the parties being held up to mutual engagements (Horton, 1997). The proposal that received the most attention, however, was the systematic description, in scholarly articles, of each author's contribution (Rennie et al., 1997). This approach allows both readers and editors to identify precisely which work was done by individual researchers. Explicitly based on suggestions made during the previous decade (Moulopoulos, Sideris and Georgilis, 1983; Saffran, 1989), the concept of "contributorship" was aimed at better distinguishing credit and responsibility, two interrelated features of authorship (Birnholtz, 2004). Such contributorship statements were the focus of experiments before they were finally introduced in the "instructions to authors" of several biomedical journals (Smith, 1997; Northridge, 1998; Rennie et al., 2000) and the recommendations of regulatory authorities, such as the International Committee of Medical Journal Editors (ICMJE) and Committee on Publication Ethics (COPE).

Linked to a conception of research activity heavily influenced by accountability, these contributorship statements allowed for both finer recognition of and responsibility for the specific tasks performed, but also assumed that the research process can be segmented into different acts that can be properly ascribed to individual contributors. The segmentation of scientific contributions was not introduced by contributorship but, rather emerged from researchers who have proposed taxonomies in response to Moulopoulos et al.'s (1983) work. These idiosyncratic taxonomies differed in the number of contributions listed (from 6 to 15) and their degree of accuracy. For example, "writing up the paper" was sometimes considered as one contribution, while in other taxonomies it was supplemented with "critical revision of manuscript", or even split into "writing the first draft of the paper", "writing later draft(s)", and "approving final draft" (Goodman 1994).

Biomedical journals were the main drivers of new taxonomies. Two peculiarities have resulted from this. First, these taxonomies are characterized by research task contributions clearly specific both to the biomedical sciences ("collecting samples or specimens", "providing DNA probes") and clinical research ("referred patients to study", "provision of study materials or patients"). Second, there is significant differences not only in the number of contributions from one journal to another, but also the variations in contribution taxonomies and their organization (Bates et al., 2004; Baerlocher et al., 2009; McDonald et al., 2010). Journals request contributions in free-text form, organized as a predefined list of research tasks to choose from, or even as hierarchical items that make some contribution roles a prerequisite for others. As these taxonomies evolve, studies have investigated the relationship between the structure of these forms, the number of contributions described, and the differences in perception among coauthors of the same article (Marušić et al., 2006; Ilakovac et al., 2007; Ivaniš et al. 2008, 2011).

Early taxonomies paved the way for large-scale empirical studies of authorship practices in science. For instance, Larivière et al. (2016) analyzed contributorship statements—divided into five contributions—for 87,002 papers published in all PLOS journals, focusing on labor distributions across disciplines, author's order, and seniority. They showed that the division of scientific labor is higher in medical research than in natural sciences, and that in it all domains but medicine, the most common task among authors was drafting and editing of the manuscript. Results of this and subsequent analyses (Macaluso et al., 2016) also showed strong distinction between tasks performed and author characteristics: younger researchers and women were more likely to perform technical contributions, whereas older, men researchers were more often associated with conceptual contributions. Authors' order was also strongly associated with number of contributions: first authors were generally associated with the vast majority of contributions, followed by last authors—who generally were not involved in technical work—and then by middle authors, whose contributions were fewer and more likely to be technical (Lariviere et al., 2016).

These findings were confirmed by Sauermann and Haeusseler (2017), who analyzed more than 12,000 articles published between 2007-2011 in PLOS ONE. As with Lariviere et al. (2016), they found that first and last authors were associated with more contributions than middle authors. In an examination of team size, they demonstrated that the number of contributions per author decreases with the number of authors but remains stable for last authors. They complemented this analysis with a survey of 6,000 corresponding authors from these papers. Their findings suggest that a majority of corresponding authors believe that contributorship statements provided more information about the contribution, but only a minority think that contributorship provides more information on the importance of contributions. Furthermore, they found that in one-fifth of papers, contributorship statements were determined by the corresponding authors alone.

Sauermann and Haeussler (2017) suggested that it was difficult to predict the contribution based on author order alone. Corrêa et al. (2017)—also using the PLOS ONE dataset—confirmed this uncertainty between authors' order and contributions made. Using a network-based approach, they found that the relationship becomes increasingly random as the number of authors per paper increases. They also provided evidence of how division of labor increases as the number of authors increases and showed that contributions can be grouped into three categories: those who write, those who perform data analysis, and those who conduct experiments.

These studies provided novel insight on the relationship between authorship and one coarse-grained contributorship taxonomy. However, the previously used five contributorship categories fail to account for the complexity of contemporary science. To address the need for a more refined taxonomy, an "International Workshop on Contributorship and Scholarly Attribution" was organized at Harvard in May 2012 at the initiative of the Wellcome Trust (IWCSA, 2012). One outcome was a pilot project involving publishers, funders, and scientists to design a cross-disciplinary standardized taxonomy for contributor roles and contribution types, which would be practicable for all scientific fields. The goal was to be interoperable with different databases and to reduce the many ambiguities that remain with earlier contributorship typologies. In the eyes of its promoters, this standardized taxonomy would not only codify the contributions of each researcher with fine granularity, allowing for specific skills to be easily identified, but would also rely on an infrastructure to manage the complex relationships between the information, its archiving and its consultation in real time.

An initial prototype comprised of fourteen types of contribution roles was designed and tested among corresponding authors of work published in various, mostly biomedical, journals (Allen et al., 2014). Based on the positive result of this experiment, a partnership with two information industry standards organizations (Consortia Advancing Standards in Research Administration Information (CASRAI) and the US-based National Information Standards Organization (NISO)) was established to achieve broader consultation and to refine the preliminary taxonomy. An updated version of the taxonomy was made public in 2015 under the name CRediT (Contributor Roles Taxonomy) to provide “a controlled vocabulary of contributor roles” (Brand et al. 2015: 154) for published research outputs.

The introduction of CRediT provides more details on the division of scientific labor than was given with previous contributorship taxonomies. First, not only may a given role be assigned to multiple contributors, but when this is the case, a degree of contribution may optionally be specified as “lead”, “equal”, or “supporting.”[1] The granularity of contribution roles is thus more precise and the same contribution role can be prioritized among contributors. Second, the fourteen contribution roles go beyond the commonly identified research tasks in traditional authorship. They notably include various roles related to research data, such as “resources” (provision of study materials, reagents, materials, patients, laboratory samples, animals, etc.), “data curation” (annotation, scrubbing and maintenance), “software” (programming, software development; designing computer programs, etc.), or “visualization” (preparation, creation and/or presentation of the published work, specifically visualization/ data presentation). Third, the writing process is divided into two main roles, “original draft” and “review and editing”, introducing nuance in this primary contributorship role. With these improvements, CRediT is suited to account for both the division of scientific labor and the allocation of individual contributions.

PLOS adopted CRediT in 2016 (Atkins, 2016). By the end of 2018, more than 30,000 articles had employed this new taxonomy. In this paper, we provide an examination of these articles to investigate whether the more fine-grained analysis provides a more nuanced portrait of division of labor than was possible with previous taxonomies. More specifically, we examine how research contributions are divided across research teams, focusing on the association between number of authors and division of labor, and on the relationship between authors’ position and specific tasks performed. We also consider the association between each of the 14 contributions, to assess whether some contributions are more likely to be performed in conjunction with others.

In their review of the taxonomy, Allen, O’Connell, and Kiermer (2019) identify how CRediT can be a useful tool in science of science. As they state: “If we can understand how collaborations work and when, or how to optimize the best team mix, then we may be able to incentivize the sorts of behaviours and activities that can bring about and accelerate discovery” (p. 74). They particularly draw attention to the issues of diversity in team composition and how contributorship studies can provide insights on how to best support women and early career researchers as they progress in science. Therefore, we also explore how the new taxonomy provides greater insight into the gendered nature of science, comparing this to the earlier PLOS typology (Macaluso et al., 2016).

[1] Although this is included in CRediT, these distinctions were not given in the data provided by PLOS for our analysis.

Dataset and methods

Launched in 2014, CRediT categorizes contributions made to scholarly papers into 14 categories (Table 1). Several journals—such as *eLife*, *Cell*, *F1000*—and publishers—*PLOS*, *Elsevier*, *Springer*, *BMJ*—have adopted it or, in the case of major publishers, have seen some of their journals adopt it. By early 2019, more than 120 journals had implemented the taxonomy (Allen, O'Connell, & Kiermer, 2019), a number that increased substantially at the end of 2019 with the adoption of the typology by 1,200 journals from Elsevier (Elsevier, 2019). Our analysis is based on one of these publishers—the Public Library of Science (PLOS)—which provided us with all of its contributorship information for papers published between 15 June 2017 and 31 December 2018 (N = 30,770). The data covered all PLOS journals and included publication date, Digital Object Identifier (DOI), journal name, author name as it appears on the paper, and associated CRediT contributions for each author.[2]

Table 1. Definition of each contribution found in the Contributor Roles Taxonomy (CRediT)[3]

Contribution	Definition
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims.
Data curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later re-use.
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyse or synthesize study data.
Funding acquisition	Acquisition of the financial support for the project leading to this publication.
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.
Methodology	Development or design of methodology; creation of models.
Project administration	Management and coordination responsibility for the research activity planning and execution.
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools.
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components.
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team.
Validation	Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs.
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation.
Writing – original draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation).
Writing – review & editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages.

[2] This made the processing of contributorships much more straightforward than what is provided through the bulk download of the full text of papers in XML format (http://api.plos.org/text-and-data-mining/). See, for instance, Larivière et al. (2016). In this case, the full names of authors were provided, along with each contribution role, thereby facilitating the author-matching process.

[3] https://casrai.org/credit/

Table 2 presents the characteristics of the dataset. The bulk of the papers were published in the megajournal *PLOS One* (87.9%), which is the second largest megajournal (Siler, Larivière and Sugimoto, 2020). Our dataset contains comprehensive data for all journals with the exception of *PLOS Biology*, for which contributorship information could only be obtained for 13 papers.[4] Important differences are observed in terms of mean number of authors per paper, with *PLOS Computational Biology* having, on average, slightly less than 5 authors per paper, while *PLOS Medicine* has almost three times the rates of *PLOS Computational Biology*. However, mean number of contributions per paper are quite constant across journals, with maximum of 11.8 in *PLOS Biology* and a minimum of 10.6 in *PLOS One*. Given the strong focus on medical sciences of the multidisciplinary journal PLOS One (Siler, Larivière and Sugimoto, 2020) and of other PLOS journals, the results need to be interpreted as illustrative of the use of the CRediT taxonomy in those disciplines.

Table 2. Number of papers published with CRediT contributions, mean number of authors and mean number of CRediT contributions per paper, by PLOS journal

Journal	N. Papers	N. Papers in WoS	% Papers in WoS	Mean N. authors	Mean N. Contributions
PLOS Biology	13	13	100%	7.2	11.8
PLOS Computational Biology	763	754	98.8%	4.9	11.1
PLOS Genetics	786	778	99.0%	8.5	11.1
PLOS Medicine	250	249	99.6%	14.2	10.8
PLOS Neglected Tropical Diseases	1,144	1,115	97.5%	9.1	11.1
PLOS One	27,057	26,398	97.6%	6.8	10.6
PLOS Pathogens	757	747	98.7%	9.4	11.0
All journals	30,770	30,054	97.7%	7.0	10.6

Contribution information provided by PLOS did not, however, contain author order; to obtain this information we had to match each PLOS paper with its record in our in-house version of Clarivate Analytics' Web of Science based on the DOI; this was feasible for 30,054 papers (97.7% of the PLOS dataset; see Table 2 for percentages by journal), which included 222,938 authorships. Once the papers were matched with the WoS, we matched each author in both data sources to obtain their individual order in the authors' list. This was first based on a perfect match of the full name string (e.g., Derek John de Solla Price = Derek John de Solla Price). However, as several names could not be matched because they were written in different manners in both databases (e.g., Derek de Solla Price, Derek J. Price, Derek Price), we performed additional matching focusing on specific parts of the name string. More specifically, we iteratively focused on the first and last 2- 5 characters of the names; this allowed us to match 221,637 authorships (99.4% of the sample).

[4] A different editorial system for *PLOS Biology* made it difficult for PLOS to provide us with the data for this journal. Therefore, while the PLOS Biology contributorship data is included in the global analysis, individual data for the journal is not provided (i.e., Figures 1 and 2).

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For this subset of authors who could be attributed an author order, we assigned a gender based on their given names. Such gender assignation of researchers has become a relatively standard practice and was shown to obtain relatively high precision and recall (Karimi et al., 2016; Santamaría & Mihaljević, 2018). In this paper, we used the algorithm developed in Larivière et al. (2013), which was created using several country-level lists of given names along with their gender. The algorithm has been tested for precision, and was found to be 98.3% precise for men, and 86.7% for women (see the supplementary material in Larivière et al., 2013 for more details). The algorithm assigned a gender to 82.2% of the authorships covered in this analysis (Table 3). This percentage varies by author order, however, with a higher proportion of last authors assigned a gender, and a lower proportion of first authors. The percentage of women authorships in the PLOS dataset represents 39.9% of authorships to which a gender could be assigned, which is slightly greater than the percentage of women authorships found in the WoS for disciplines of the medical sciences (about 35%).

Table 3. Number of authorships with gender assigned, by author order

Gender	First		Middle		Last		Any order	
	N	%	N	%	N	%	N	%
Gender assigned	26,005	79.9%	129,198	82.3%	27,064	84.4%	182,267	82.2%
Female	12,094	37.2%	52,106	33.2%	8,600	26.8%	72,800	32.8%
Male	13,911	42.7%	77,092	49.1%	18,464	57.6%	109,467	49.4%
Initials	382	1.2%	2,085	1.3%	447	1.4%	2,914	1.3%
Unisex	704	2.2%	3,899	2.5%	911	2.8%	5,514	2.5%
Unknown	5,462	16.8%	21,847	13.9%	3,633	11.3%	30,942	14.0%
Total	32,553	100.0%	157,029	100.0%	32,055	100.0%	221,637	100.0%

Results

Figure 1 presents, for each PLOS journal, the percentage of papers on which each contribution appears. This provides an indication of importance of each task across the spectrum of PLOS journals and, conversely, of the tasks that are not performed by any of the authors on a given paper. Nearly all papers had an author writing the original draft (99%), as well as authors reviewing and editing (96%) and conceptualizing (95%) them. This suggests that these remain essential research acts—all papers are conceptualized and written. The percentage of papers with at least one author contributing to formal analysis (91%), methodology (90%), and investigation (86%) are also very high, suggesting that empirical papers are the bulk of those published in these journals. 84% of papers contain the supervision task; the 16% of papers without such task likely do not include trainees as co-authors. Data curation is present in 79% of papers—although this percentage is higher in journals like *PLOS Medicine*—and 70% of papers contain project administration and funding acquisition, with latter task accounting for a higher percentage in *PLOS Pathogens* and *PLOS Genetics*. Resources, Validation and Visualization are present in about half of all papers. Software contribution appears in less than 40% of papers, except in *PLOS Computational Biology* where it is found in almost three-quarters of papers.

Figure 1. Percentage of papers with specific CRediT contribution, by journal (30,054 papers published in 2017 and 2018)

Contribution	PLOS Computational Biology	PLOS Genetics	PLOS Medicine	PLOS Neglected Tropical Diseases	PLOS One	PLOS Pathogens	All PLOS journals
Writing - Original Draft	99%	100%	100%	99%	99%	98%	99%
Writing - Review & Editing	96%	97%	100%	98%	96%	97%	96%
Conceptualization	97%	99%	100%	98%	95%	98%	95%
Formal analysis	89%	90%	99%	95%	91%	91%	91%
Methodology	91%	86%	94%	93%	89%	88%	90%
Investigation	86%	96%	82%	90%	85%	96%	86%
Supervision	85%	91%	85%	90%	84%	92%	84%
Data curation	65%	75%	89%	79%	80%	68%	79%
Project administration	63%	71%	72%	75%	70%	74%	70%
Funding acquisition	79%	90%	76%	79%	68%	91%	70%
Resources	50%	61%	50%	67%	57%	68%	57%
Validation	61%	57%	50%	59%	55%	57%	55%
Visualization	71%	59%	50%	56%	51%	56%	52%
Software	74%	37%	38%	35%	39%	22%	39%

In order to assess division of labor across authors, we compiled, for each journal, the percentage of authors who performed a given contribution. As shown in figure 2, the majority of authors contribute to writing – review and editing (68%), as well as methodology (55%), investigation (53%) and conceptualization (51%). Worth mentioning is the fact that 95% of authors from *PLOS Medicine* have contributed to the review and editing of the manuscript; this is likely due to the second criteria of the ICMJE which states that all authors should have "[drafted] the work or revising it critically for important intellectual content" (International Committee of Medical Journal Editors, 2019, p. 2). All other CRediT contributions were, on average, performed by a minority of authors. Formal analysis, data curation and validation were, on average, performed by 42%-45% of authors across all PLOS journals, with higher percentages of authors contributing to formal analysis at *PLOS*

Computational Biology, and *PLOS Genetics*, as well as higher share of authors contributing to validation at *PLOS Computational Biology*. Contrary to what was observed in the previous typology used by PLOS (Larivière et al., 2016), where more than half of authors (and as much as 80% in social sciences and physics, among others) had "written the paper", the writing of the original draft is a contribution done by a much narrower percentage of authors (39% across all PLOS journals). Tasks typically performed by principle investigators (resources, supervision, project administration and funding acquisition), as well as contributions than can be considered to be more specialized (visualisation and software) are performed by a minority of authors (between 31% and 38%), with higher percentages of visualisation and software for *PLOS Computational Biology*.

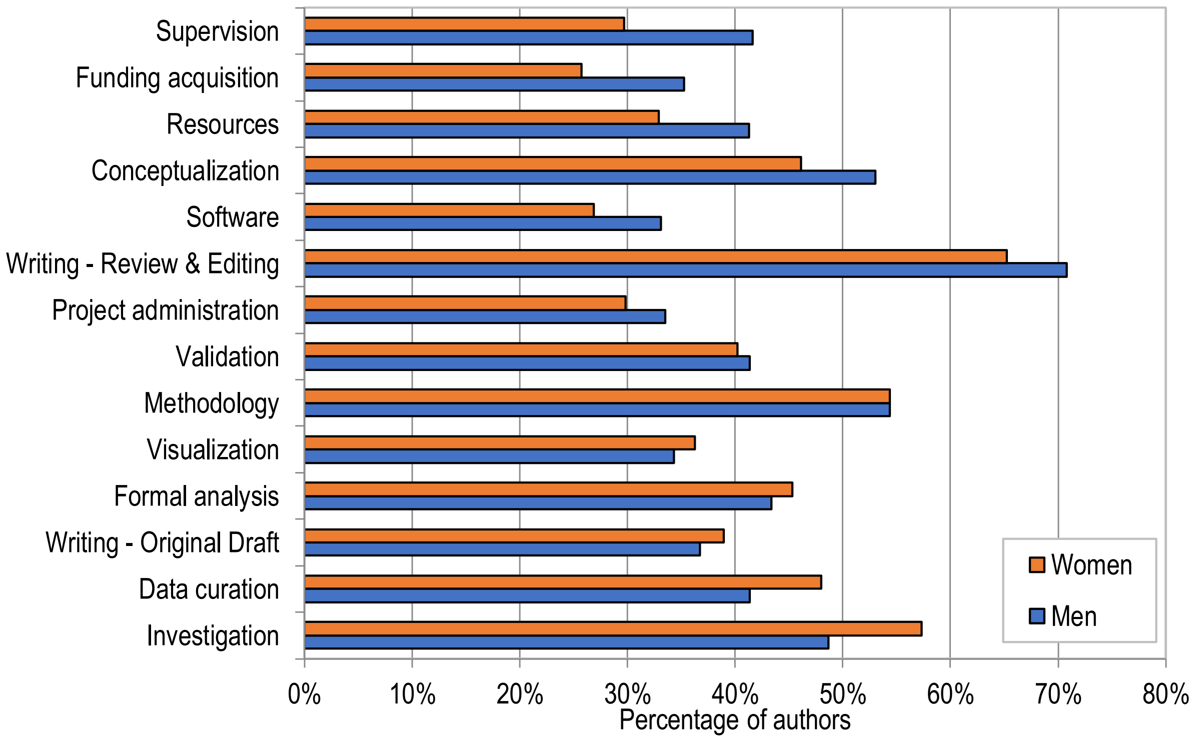
Figure 2. Percentage of authors who performed a given CRediT contribution (when contribution appears on the paper), by journal (30,054 papers published in 2017 and 2018)

Contribution	PLOS Computational Biology	PLOS Genetics	PLOS Medicine	PLOS Neglected Tropical Diseases	PLOS One	PLOS Pathogens	All PLOS journals
Writing - Review & Editing	81%	60%	95%	70%	68%	52%	68%
Methodology	63%	53%	58%	54%	55%	50%	55%
Investigation	59%	61%	52%	54%	52%	56%	53%
Conceptualization	65%	44%	51%	45%	51%	38%	51%
Formal analysis	51%	51%	33%	41%	45%	46%	45%
Data curation	45%	45%	41%	42%	45%	42%	45%
Validation	52%	39%	37%	37%	42%	34%	42%
Writing - Original Draft	56%	37%	26%	34%	39%	31%	39%
Resources	42%	36%	30%	36%	38%	32%	38%
Visualization	43%	36%	24%	32%	37%	31%	36%
Supervision	42%	29%	35%	34%	37%	25%	36%
Project administration	36%	24%	33%	29%	33%	22%	33%
Software	43%	27%	23%	25%	33%	22%	33%
Funding acquisition	41%	28%	31%	27%	31%	24%	31%

Figure 3 shows the percentage of men and women, respectively, who have performed a specific CRediT contribution. The newly adopted taxonomy reinforces some of the initial findings for gender, particularly the gendered divide between conceptual and empirical work: while 57% of women contributed to the investigation, this percentage is of 49% for men. A similar gap is also observed for data curation. Men, on the other hand, are more likely to conduct tasks associated with seniority, such as funding acquisition and supervision (30% more likely than women), contributing resources, software, conceptualization, and project administration. While such differences are likely influenced by the fact that women academics are on average younger than men (McChesney and Bichsel, 2020), other studies have shown that gender differences in contributions remained constant with age as well as with the number of authors per paper (Macaluso et al., 2016).

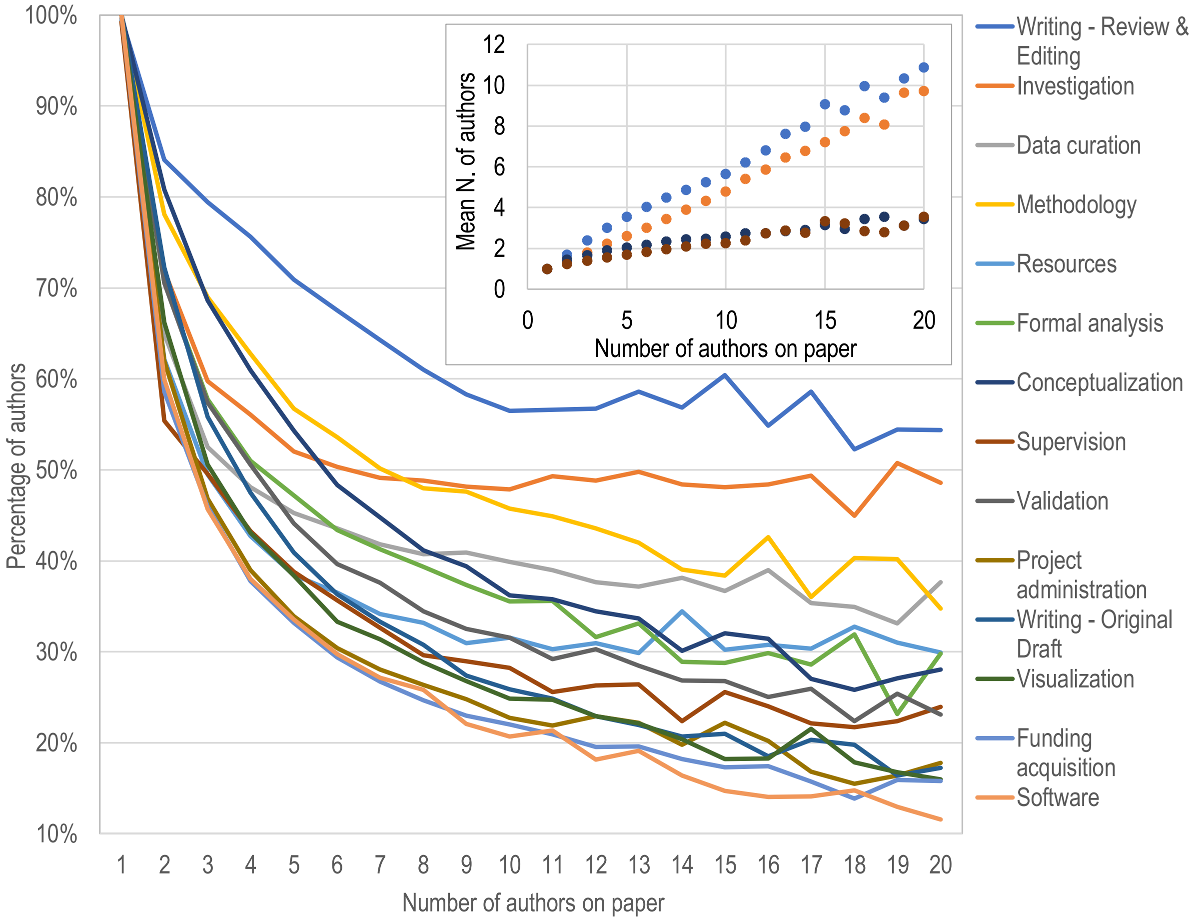
A striking feature of CRediT compared to previous studies based on the PLOS typology (Macaluso et al., 2016) is in the writing of the manuscript. Using the previous PLOS typology, it appeared that men dominated in the writing of the manuscript. However, the nuanced division between writing the original draft and doing reviewing and editing demonstrated a delineation between labor roles for men and women: women are 6% more likely to have written the original draft; whereas men are 8% more likely to review and edit the manuscript. While those differences are not necessarily sizeable, the fact that we observe a clear inversion of leading genders in the two contributions associated with writing is quite striking. This also demonstrates that the original finding obtained in Macaluso et al. (2016) was skewed by the ubiquity of the "review" portion of writing. Once the taxonomy isolated original drafting of the text, the contribution of women as more likely to write the original draft emerges. This suggests that the more nuanced taxonomy lends greater insight into contrasted divisions of labor.

Figure 3. Percentage of men and women authors who have performed a specific CRediT contribution (30,054 papers published in 2017 and 2018)



Division of labor, furthermore, varies as a function of numbers of authors. Figure 4 presents the percentage of authors who have performed a given task, for papers between 1 and 20 authors (n=29,689 papers, 96.5% of the dataset). Obviously, for single authored papers, 100% of tasks are performed by a single author. As the number of authors increases, tasks are increasingly divided—although the extent to which they are varies as a function of the tasks involved. In other words, while some tasks are performed by a smaller proportion of authors as the number of authors increases, other tasks remain relative stable once a certain threshold is met. For instance, the writing – review and editing task remains performed by a high percentage of authors (i.e., more than half of authors), even when there are 20 authors on a paper. In a similar manner, the proportion of authors who contribute to investigation stabilizes once 10 authors are reached with, again, about half of authors contributing to the task. Other tasks, however, are increasingly divided as the number of authors increases. For instance, the proportion of authors who perform supervision and writing of the original draft—among others—decreases steadily as the number of authors increases, which suggest, as shown in the inset, that these tasks remain performed by a few authors. More specifically, even in papers by 20 authors, between 3 and 4 authors have been involved in those two tasks.

Figure 4. Percentage of authors who performed a given CRediT contribution, by number of authors, for papers between 1 and 20 authors (n=29,689 papers). Inset: mean number of authors who performed a subset of CRediT contributions (writing – review and editing, investigation, writing – original draft, and project administration)



As shown with the previous PLOS typology, there is a strong relationship between authors' order and tasks performed (Larivière et al., 2016; Sauermann & Haeussler, 2017). Figure 5 presents the percentage of authors who have performed a given CRediT contribution, as a function of their order on the byline of the article (first, middle, last). Taken globally, the figure shows an inverse relationship between the tasks performed by first authors and the tasks performed by last authors. More specifically, first authors are much more likely to write the original draft of the manuscript, curate the data, perform the formal analysis, visualization and investigation, as well as contribute to the methodology. Globally, the mean number of tasks to which first authors contribute is higher for first authors, followed by last authors, and then by middle authors. Last authors, on the other hand, are much more likely to have contributed to supervision, funding, resources, and project administration. Conceptualization, and reviewing and editing of the manuscript, are performed by both first and last authors in relatively similar proportions, although last authors are slightly more likely to have performed the tasks. There are no tasks that middle authors are more likely to perform than first and last authors. However, there are a few tasks where their participation is relatively more important: they are more likely to contribute to supervision and to resources than first authors, and more likely to contribute to data curation, investigation and software than last authors.

Figure 5. Percentage of authors who performed
CRediT contribution, by author's order

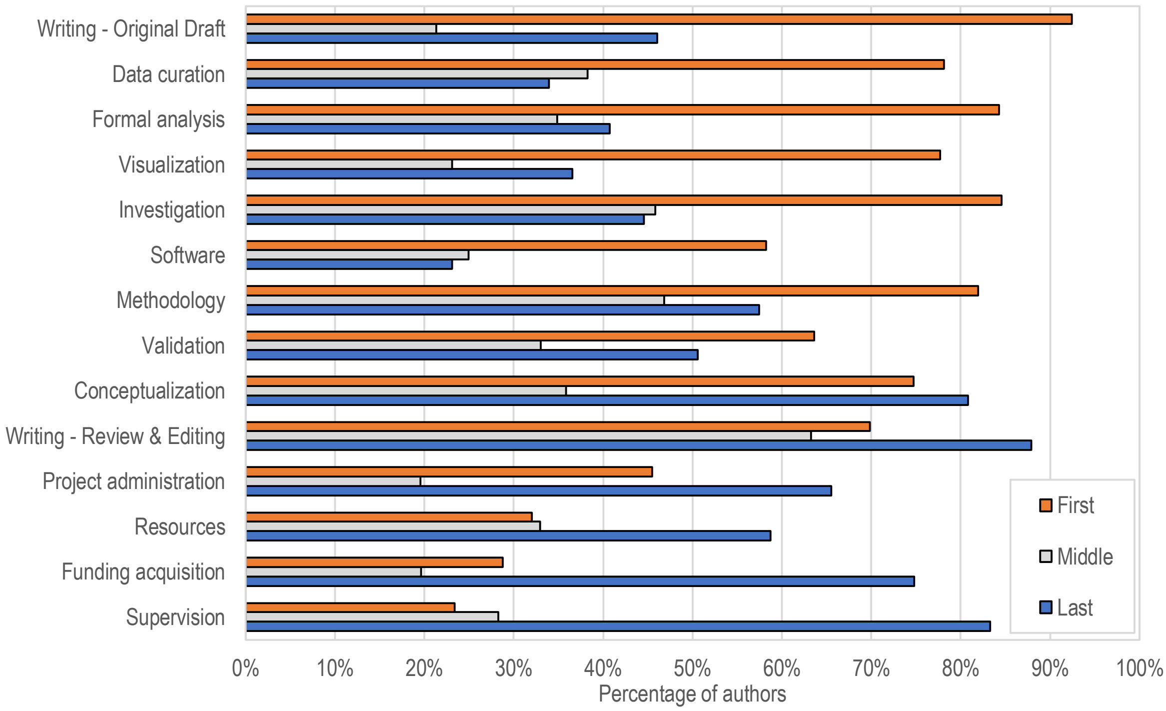


Figure 6 presents the contributions that are the most likely associated with each other (i.e., performed by the same authors), as well as the asymmetry of these relationships. More specifically, it shows the percentage of authors who have performed contribution A who have also performed contribution B. For example, the figure shows that, while 93% of authors who have contributed to the funding acquisition have reviewed and edited the manuscript, only 46% of authors who reviewed and edited the manuscript have acquired funding. This relationship is among the most asymmetrical, along with software, project administration, visualisation, resources and supervision, on the one hand, and their relationship with reviewing and editing the manuscript. That is not surprising: writing and editing the manuscript is a task that most authors perform, irrespective of their other contributions to the manuscript. At the other end of the spectrum, funding acquisition is the contribution that has the lowest relationship with other tasks, except with supervision and project administration. A similar phenomenon is observed for supervision, project administration and resources. Software also has little relation with other tasks, except for visualization.

Figure 6. Percentage of authors who have performed contribution A who also have performed contribution B

Contribution A \ Contribution B	Funding acquisition	Software	Supervision	Project administration	Resources	Visualization	Writing - Original Draft	Validation	Data curation	Formal analysis	Investigation	Conceptualization	Methodology	Writing - Review & Editing
Funding acquisition		68%	85%	82%	83%	74%	79%	79%	76%	77%	81%	90%	84%	93%
Software	70%		71%	74%	79%	82%	81%	83%	86%	89%	85%	83%	90%	89%
Supervision	74%	61%		76%	74%	69%	75%	75%	69%	71%	75%	85%	79%	91%
Project administration	80%	68%	83%		80%	75%	80%	79%	78%	78%	83%	89%	85%	92%
Resources	72%	65%	74%	73%		67%	70%	73%	72%	70%	77%	78%	79%	88%
Visualization	65%	77%	67%	71%	72%		83%	85%	83%	87%	85%	83%	88%	91%
Writing - Original Draft	62%	69%	61%	67%	65%	76%		76%	78%	82%	82%	84%	85%	90%
Validation	60%	66%	67%	65%	67%	73%	73%		75%	78%	80%	78%	83%	88%
Data curation	53%	64%	52%	58%	60%	67%	67%	68%		76%	78%	70%	77%	81%
Formal analysis	51%	65%	51%	56%	57%	68%	70%	69%	75%		76%	72%	80%	83%
Investigation	48%	57%	49%	54%	56%	60%	62%	63%	69%	68%		67%	75%	78%
Conceptualization	59%	52%	63%	60%	60%	58%	66%	64%	62%	64%	68%		76%	86%
Methodology	48%	54%	52%	52%	54%	57%	61%	62%	63%	67%	71%	72%		81%
Writing - Review & Editing	46%	42%	52%	47%	50%	48%	56%	55%	53%	56%	60%	66%	65%	

Discussion

Our analysis has delved into the ways in which scientific labor is accounted using a more refined contributorship taxonomy than was previously available. While confirming several previous findings (Lariviere et al., 2016; Sauermann & Haussler, 2017; Corrêa et al., 2017), the research has provided novel information on the composition and distribution of labor across teams. For example, contributorship information reveals the types of labor that are critical for producing scientific research: almost all research articles include conceptualization, operationalization, and communication through writing. Deviations by discipline, however, reveal the importance of other more niche tasks such as visualization and software, acknowledged in certain domains. These findings suggest greater heterogeneity in evaluation processes to attend to the importance of tasks by discipline. Privileging one type of labor will inevitably lead to inequities across disciplines, where specific tasks performed remain either non-performed, or unacknowledged through authorship and contributorship. Furthermore, both the heterogeneity of labor types and the number of contributions per paper suggests that mentoring and doctoral education may need to be reconfigured to address the changing composition of team science (Sugimoto, 2016).

The bureaucratization of science can be considered as an inevitable consequence of the ubiquity of collaborative science (Larivière et al., 2015). As team size increases, the mean number of authors contributing to investigation, for instance, also increases, which suggest that the expansion of teams is largely a function of the increasing number of researchers who contribute to technical tasks, and of the acknowledgement that this contribution warrants authorship (Shapin, 1989). This is not associated with a concomitant rise in those who have written papers' first drafts or supervisors: there can only be a few supervisors and original authors, but there is a constant expansion in other forms of labor, recognized through authorship (Pontille, 2016). As Shapin (1989) observed: "Scientists' authority over technicians typically means that it is the former who decide how officially to arrange the relationship, whether to "make them" authors or coauthors, what counts as genuine knowledge as opposed to mere skill, and what technicians' work signifies in scientific terms" (p. 562). Our research suggests that, despite the steep increase in number of authors, the number of scientific leaders remains small (Robinson-Garcia et al, 2020). Such division of labor and capital reinforces scientific hierarchies and cumulative advantages (Merton, 1968). Our investigation of the current multiple authorship practices and contributorship distributions illuminates the selective attribution process among coauthors, wherein having one's name in an article byline does not equate or result in leadership positions. Consequently, the growing proportion of "supporting authors" (Milojevic, Radicchi, & Walsh, 2018) has strong implications for the composition of the scientific workforce.

The high proportion of data curation—present in 79% of papers—draws attention to a heavily overlooked labor role in science. The majority of articles involve this task, but there is relatively little training provided to doctoral students, nor are many scientists prepared to engage in this. With the increasing prevalence of calls for open science (e.g., McKiernan, 2016), it is essential that data be properly curated for better sharing and transparency. For example, several countries have established policies requiring the sharing of data created through funded research. Interviews with scientists, however, have revealed strong social and technical challenges to fulfilling these mandates (e.g., Borgerud & Borgerud, 2020). Data curation work continue to be widely under-resourced, despite increasing calls for data transparency (Leonelli, 2016) and the overwhelming importance of this work, as demonstrated by our analysis. Future work should ensure that data curation is both valued and supported in research environments.

Women are more likely to be associated with this data curation, as well as other technical work, such as investigation, which confirmed results obtained in previous analyses (Macaluso et al., 2016). However, CRediT provided a much more nuanced way to evaluate the conceptual vs. technical divisions identified in earlier research (Macaluso et al., 2016). Furthermore, and perhaps more importantly, the taxonomy elucidated a key difference in one of the main contribution types: writing. Whereas the original five categories contained a single writing category, where men dominated, the new classification distinguished between the editing and reviewing and the much more labor-intensive writing of the first draft. In this distinction, the role of women emerged starkly. Given that they are underrepresented in first and last authorships, this is particularly striking and speaks to some of the underlying injustices in the division of labor and calculation of production (Rossiter, 1993; Penders & Shaw, 2020). This can be critical for the career of women and other underrepresented minorities. As sociologist Mary Frank Fox (2005) observed: "…until we understand factors that are associated with productivity, and variation in productivity by gender, we can neither assess nor correct inequities in rewards, including rank, promotion, and salary […] because publication productivity operates as both cause and effect of status in science […] productivity reflects women's depressed rank and status, and partially accounts for it." It is no surprise, therefore, that junior scholars were the most concerned about their representation in contributorship statements and expressed the greatest desire for broad participation in these discussions (Sauermann & Haeussler, 2017). There is a considerable need for greater transparency about the career lifecycles and interoperability between systems (Canibano et al., 2020). The integration of CRediT and ORCID is a useful start to this.

It is clear from the data that contributorship provides a lens to add greater transparency in the capital exchange for authorship. In addition to providing greater accountability for research, contributorship also sheds greater light on the flaws in the current system. Our work demonstrates a clear division of labor as team size increases and the corresponding isolation of certain contribution types. While this facilitates efficiency and may be necessary for certain types of research, it inevitably increases the chances of potential misconduct, mistake, or fraud, given that several team members provide their contributions without direct oversight[5]. One critical role, therefore, may be validation. However, this was present in only 55% of papers (performed by 42% of authors). One may argue that this is merely idiosyncratic interpretations of the contributorship roles, where some authors may consider validation a part of the "investigation" or "formal analysis". However, the task definition is clear: "verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs." The lack of validation in the PLOS papers reinforce the concerns of the "reproducibility crisis" (Baker, 2016). To address this, journals could require validation as a mandatory contribution type for empirical work. Contributorship statements are not without limitation. One strong concern at present is the assumed relationship between the actual labor and the indicator of this labor in contributorship statements. Undoubtedly, when scholars mutually ascribe the different tasks of CRediT to themselves, they maintain the opacity necessary to favor good working relationships between colleagues and teams. Since criteria for authorship vary considerably across disciplines (Pontille, 2004, 2016; Paul-Hus et al., 2017), so too might be for the interpretation of contribution roles. More research is necessary to understand whether CRediT provides a valid representation of the work.

Another related general concern has simultaneously been raised by some clinical researchers and regulatory bodies regarding these expansive categories: if contributorship removes "much of the ambiguity surrounding contributions, it leaves unresolved the question of the quantity and quality of contribution that qualify for authorship" (International Committee of Medical Journal Editors, 2019). As with any system tied to capital, there is likely to be goal displacement as the taxonomy gains wider acceptance and use. For example, the disproportionately high degree of *PLOS Medicine* authors associated with writing and editing may be less a disciplinary difference and more an adherence to the ICMJE criteria. And, as some critically emphasized, the contributorship procedure favors pharmaceutical firms that, without having to pretend to intervene intellectually by figuring in an article byline, could now become "contributors" and thus avoid allegations of conflicts of interest (Matherson, 2011). This suggests that authors may modify their behavior in order to meet certain requirements, norms, or incentives. Further investigations are thus needed to explore such issues.

Despite the accountability it aspires to, any description of scientific contributions, even the fine-grained provided by CRediT, can never be complete. As Sauermann and Haeussler (2017) noted, contributorship statements may reduce misconduct while simultaneously leading scientists to avoid association with those tasks with a greater potential for risk. Scientists may also begin to adopt similar practices of ghost, guest, and gift authorship to contributorship. The systematic description of work does not, therefore, preclude invisibility, but only displaces it elsewhere. As a consequence, it leaves ghostwriting of articles and potential honorary contributorship in the backrooms of scientific research. Contributorship statements are not a panacea for the problems of authorship misconduct; however, they do

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[5] Some journals (e.g., BMJ) identify a role for a "guarantor", who will take responsibility for the entire manuscript. This is also the implied role taken by many corresponding authors. It is not, however, made explicit and is not easily defensible in misconduct cases.

contribute to clarifying the contributions that are sufficiently important to warrant authorship from those that are not. Issues with authorship are not an indication of problems inherent with the contributorship model, but symptomatic of a larger structural problem in the contemporary scientific community, which is the demand, by both policy-makers and researchers themselves, for *procedural ways* of assessing excellence and scientific performance.

Conclusion

Over the last few decades, transparency in authorship and scholarly publishing have become increasingly discussed in academe. This is due to several interrelated phenomena. First, bibliometric evaluations have become widespread across all countries, and have been applied to the promotion of individual researchers (Quan, Chen, and Shu, 2017) and to institutions, mostly through the ever-expanding university rankings (Debackere and Glänzel, 2004). Secondly, the rise in the number of PhD graduates, linked with the relative stability of faculty positions, is increasing the competition among new graduates, who are ever more aware—as this is often made explicit—that publications are the currency that will allow them to find a position. The pressures wrought by this system have led to several authorship malpractices. There are flagrant acts of "civil disobedience" in authorship, such as adding humorous fictional co-authors, pets, or celebrities to a paper (Penders & Shaw, 2020). However, some new authorship issues are more pernicious, such as adding children as co-authors so that they can begin to build their publication record (Zastrow, 2019), and the growth of predatory publishing (Grudniewicz et al., 2019) and publication bazaars (Hvistendahl, 2013). These latter actions demonstrate how critical authorship is for the reward structure of science and the misconduct that can arise as a result of these pressures to publish.

By fragmenting scientific production process into clearly distinct tasks, CRediT was designed to transcend the customary rules specific to name orderings in scientific publications. Information about the conditions of production of research being made available in each scientific article, the systematic description of contributions according to CRediT is not limited to the authorship practices of a particular discipline. On the contrary, it can easily be adjusted to various kinds of division of scientific labor and their specific hierarchical principles across research teams (e.g., a team led by a leader, a project carried out among peers, a multicenter research project). In other words, CRediT is not at odds with the distinct authorship practices in place across disciplines. Rather, based on the traceability of individual performance, it provides additional information on the attribution process. Simultaneously, as other accounting devices (Strathern, 1999), the systematic description of contributions, especially through CRediT, comes with ambivalence. While it undoubtedly introduces greater transparency in both reward and accountability related to the division of labor involved in a published article, it simultaneously fuels a regression of trust at the root of scientific relations (Pontille, 2015). Put differently, the beneficiaries of the information made available–especially women and junior scholars–, may become the potential victims of devices that facilitate monitoring and surveillance at the heart of scientific activity.

All these elements have one point in common: the (sole) emphasis on scholarly publications as the criteria for research excellence. It seems that, along the way, we have forgotten what drives researchers to do what we do, and why our societies have made the choice to support us in this endeavour, which is to discover new things. We have replaced a "taste for science" by a "taste for publication" (Osterloh & Frey, 2014). As per Gingras (2018), the meaning of scholarly publications has changed from a unit of (new) knowledge produced, to an accounting—or accountability—unit. Directly related to CRediT, "the systematic description of contributions leads toward accounting management for scientific activity. […] As a divisible, accounting unit, each scientific act may even be associated with a specific amount" (Pontille, 2016: 122). In this way, contributorship does not dismantle performance-based rewards (Debackere and Glänzel, 2004; Sivertsen, 2009), but rather serves to bring greater precision in accounting.

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Data availability

The PLOS dataset can be downloaded from https://doi.org/10.6084/m9.figshare.13277168.v1