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Understanding researchers' Twitter uptake, activity and popularity—an analysis of applied research in Germany

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Abstract
Social media is opening up new avenues for disseminating research outputs. While prior literature points to the essential role of Twitter in this context, evidence on what determines variation in researchers´ Twitter engagement remains scarce. In this account-level study of Twitter usage, we consider how research productivity, research quality, and participation in academic conferences relate to Twitter uptake, activity and popularity, while also taking into account differences between academic disciplines. We use a population sample comprising data on Twitter engagement of researchers employed at the Fraunhofer-Gesellschaft, Europe´s largest applied research organization. We find that participation in academic conferences is strongly associated with Twitter uptake and popularity, but not with Twitter activity as such. We also find positive associations between research productivity and Twitter uptake as well as between research quality and popularity. Moreover, physicists use Twitter more than researchers from other disciplines, female researchers use Twitter less, and scientific age is negatively associated with Twitter activity. Our findings contribute to the literature on academic social media usage by providing indications for both push and pull mechanisms at play within social media research dissemination.

Keywords Twitter · Research dissemination · Citation impact · Altmetrics, academic conference

Introduction

Increasingly, researchers use social networks, especially Twitter, to stay informed about new ideas in the community and to disseminate their work—a novel approach quite different from conventional channels of scientific communication. Tweets about scientific articles have become an important altmetric for research impact over the last years (Ke et al., 2017). At the same time, the proposition of a "Kardashian index" for scientists receiving excessive attention on social media (Hall, 2014; You, 2014) was an early indication of a potential disconnect between the scope and quality of researchers' academic work and their activity on social networks. While repeatedly, small but positive associations have

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been observed between the attention research papers receive on Twitter and their citations (Mohammadi et al., 2018), there is no clear relationship between academic activity and Twitter usage (Ferreira, Mongeon, and Costas 2021). Moreover, many tweets by scientists might remain mechanical and devoid of original thought (Robinson-Garcia et al., 2017). To date, about 10% of scientific Twitter users produce 80% of all activity and it is unclear whether these are scientifically relevant or just very active persons (Yu et al., 2019).

Research has shown that scientists use Twitter both for gathering inputs and disseminating their work (Klar et al., 2020; Mohammadi et al., 2018). An important aspect of social media and Twitter usage in science may be that it complements the traditional pull model of research dissemination, where researchers depend on publishers to "pull their research in", with a push model, where researchers more actively promote and disseminate their work and thus gain stronger agency (Allen et al., 2013; Klar et al., 2020). However, Twitter usage and activity vary between disciplines (Ke et al., 2017; Sugimoto et al., 2017, Torres-Salinas, Robinson-García, and Arroyo-Machado 2022) and depend on a number of other contextual factors (Yu et al., 2019). As recent research has documented, it is empirically challenging to capture the true extent of research dissemination via Twitter in a valid manner. Even the amount of pertinent tweets issued depends on a number of structural, circumstantial and idiosyncratic conditions, rendering it unfit to "measure either popularity or impact" (Yu et al., 2019: 841).

As it remains unclear whether the increased use of Twitter and other social networks indicate a transformation of how research is disseminated, our analysis takes a step back to study how researchers use Twitter from a more fundamental perspective. As a first step into assessing social media's emerging role in and for science, we establish what kinds of researchers appear more inclined to publish their research on Twitter, as measured by their maintaining Twitter accounts (uptake), by their level of activity on Twitter as measured by the numbers of their tweets and re-tweets, and their popularity as measured by the numbers of their followers and the public lists including them. From a conceptual perspective, these account characteristics denote necessary conditions of the process of research dissemination via social media—rather than its successful completion (Allen et al., 2013).

In order to avoid distortions by individual 'Twitter stars' among scientists and unequal representation of Twitter users in different scientific environments (Yu et al., 2019), we reverse the perspective and study a population of more than 15,000 researchers at Fraunhofer-Gesellschaft; the largest applied research organisation in Europe. This population comprises more than 800 researchers with Twitter accounts and many non-users of Twitter. On this empirical basis, we analyse how traditional measurements of research productivity and quality relate to Twitter uptake and activity of researchers and their popularity on Twitter. Moreover, we consider whether academic conferences, as real-world events providing occasions to tweet, relate to the characteristics of their Twitter accounts.

With our analysis of Twitter uptake and activity of researchers and their popularity, we add to the understanding of social media use in science and demonstrate that the necessary foundations for the heralded shift to a push model of research dissemination are far from being consistently in place. Rather, there is a mix of push and pull factors at play. Researcher's current Twitter activity may be best understood as being motivated by a mix of different mechanisms, in particular regarding researchers' Twitter uptake and their popularity, which are driven, amongst other factors, by occasions to tweet arising from the participation in academic conferences. Further contributions are related to our use of an innovative methodology to derive and analyse a unique population dataset combining data on twitter activity and bibliometric information on Fraunhofer researchers. Importantly, our dataset also includes researchers not using Twitter, enabling a control for self-selection

issues in our subsequent analysis. On that basis, we subject scientist's social media usage to a more robust empirical test than most other recent studies of tweeting scientists, which often have to rely on much smaller and less than representative convenience samples (Sugimoto et al., 2017). Moreover, our work complements current methodological contributions on automated approaches for charting twitter usage and the publishing activities of large swathes of researchers (Costas et al., 2020).

The following section reviews the literature on tweeting researchers and, more broadly, academic research dissemination via Twitter. The third section develops the analytical framework and expectations regarding the relationships between research productivity and Twitter usage and popularity, and the impact of differences in academic disciplines on these relationships. The fourth section presents the dataset and the empirical strategy, and the fifth section presents the results. The sixth section discusses the findings and the seventh section concludes.

Literature review

In research, who tweets, and why?

Twitter is a micro-blogging service that allows users to post short messages and files. Founded in 2006, it is by far the most popular service of its kind. A 140-character limit on the length of Twitter posts was raised to 280 characters in 2017. In a comprehensive literature review, Sugimoto and colleagues (2017) found that rates of scholarly Twitter use vary between 5 and 32%. Two years later, Yu et al. (2019) identified 2,6 million academic Twitter users, amounting to scarcely 1% of all Twitter users and further qualified by the fact that 10% of these users contribute 80% of all tweets within this group. Academic Twitter users that tweet more might also be more likely to share information rather than expressing opinions, as a study of Astrophysicists tweeting behaviour indicates (Holmberg et al., 2014). Twitter is one of many sources of altmetrics derived from social media data, and differs from other sources such as Scopus, Web of Science, Academia.edu or Mendeley in having a stronger focus on facilitating social networking, and a lesser focus on scholarly activities (Wouters, Zahedi, and Costas 2019).

Given the analytical objectives of this paper, two aspects are of particular relevance: existing findings on the relation of the characteristics of researchers and their Twitter uptake, activity and their popularity on Twitter, and existing findings on their motives for using Twitter. This focus differs from much of the literature relating to Twitter and the production of scientific knowledge conducting analyses at the level of scientific publications and tweets, rather than individual researchers and Twitter accounts (Bornmann & Haunschild, 2018; Eysenbach, 2011; Wang et al., 2016).

A recent study presenting matching algorithms for identifying Twitter users among researchers from the Web of Science analysed around 300,000 accounts and found that more than 40% of researchers on Twitter are affiliated with US or UK institutions. The biggest share of researchers is in biomedical and health sciences, whereas, in terms of total numbers, most tweeting researchers are from the social sciences and humanities (Costas et al., 2020). This study also finds that more senior researchers might be more likely to use Twitter, however, since the matching algorithm presented in this study performs better at identifying researchers with more publications, that particular finding could be a methodological artefact.

More evidence on discipline-specific differences in Twitter usage is provided by a survey of around 2,000 users finding that 37% of respondents identify themselves as belonging to social science disciplines and 22% as belonging to the humanities (Mohammadi et al., 2018). One aspect limiting the interpretability of these findings is that this survey includes both academic and non-academic respondents, meaning that the findings concern both active researchers and individuals in other professions who have an academic background. Another study of around 45,000 users identifies the disciplines of tweeting academics by first developing a list of titles for scientific disciplines and then searching for these titles in lists that users can create to organize the accounts that they follow. Twitter accounts included in user-created lists that match the title of a scientific discipline are assumed to belong to that discipline (Ke et al., 2017). According to this study, historians, psychologists, physicists and nutritionists are among the academics using Twitter the most. However, a recent study covering 16 countries using a dataset from *Altmetric.com* in which tweets play a dominant role shows that the share of scientific publications for which altmetric data exists is highest for the disciplines of Space Sciences and Molecular Biology & Genetics (Torres-Salinas, Robinson-García, and Arroyo-Machado 2022). These contrasting results might suggest that discipline-specific variation in the salience of altmetrics such as Twitter might be affected by the methods of data collection used, but even more, that different disciplines tend to rank higher when looking at the total numbers of social media activity than when relating this activity to the size of the discipline.

Regarding the motivations for Twitter usage, existing research reports that academics use Twitter for many reasons. According to the findings of Mohammadi and colleagues (2018), obtaining (73%) and sharing (66%) real-time information and the expansion of professional networks (64%) are the most prominent motives for Twitter usage in a sample containing both academics and non-academics. However, communicating about academic events (52%) and communicating research results to the public (47%) as well as to peers (43%) also are important motives for Twitter usage (ibid.). Likewise, Holmberg and Thelwall (2014) found in a study of tweets from highly productive researchers that most of their tweets are not or not clearly about science. The URLs shared by academics indicate a somewhat similar trend; with Instagram, Facebook, Twitter and YouTube ranking on top, followed by the news websites of the Guardian and the New York Times (Ke et al., 2017). The most prominent science related domains are those of the Nature Publishing Group and major academic publishers such as Wiley and Springer.

From the aforementioned prior research, it can be deduced that there are at least two modes of academic Twitter usage. First, researchers might seek to communicate or exchange information about new research results. This kind of Twitter usage is related to scientific output and comprises all Twitter activity related to new publications and ideas. The second kind of Twitter usage is occasional and relates to academic events and conferences. Twitter provides a backchannel for conferences, where conference hosts and attendees can socialize, exchange ideas and share information about the current event and their activities there (Wen et al., 2014; Letierce, Passant, and Decker 2010). Hence, real-life scientific events might provide an occasion for scientific tweets. In practice, these output-linked and occasional forms of academic Twitter usage overlap, as the presentation and discussion of research results is a core purpose of conferences. Conceptually, however, their distinction allows us to recognise that both research productivity and academic social events might structure Twitter usage in different ways.

To summarize, the extant literature indicates that, geographically, academic Twitter usage is most prevalent in the Anglo-Saxon world (Yu et al., 2019), and regarding academic disciplines, it is most frequent in biomedical and health sciences (in relative terms)

and in social sciences and the humanities (in absolute terms). However, our knowledge about both what types of scientist are most likely to use Twitter and for what purpose they do so remains limited. Most existing studies on the characteristics and motivations for researchers using Twitter are either not based on large random samples at all or on rather broad reference samples not focused on professional researchers, but rather on "scientific Twitter users" users with varying backgrounds. Yet, we can distinguish two forms of academic Twitter usage, one related to research output, and one related to real-life scientific events both of which will subsequently be adressed in our guiding research questions. At the same time, existing evidence indicates that tweeting about research may not be the most prevalent thing that academics do on Twitter, and researchers might have "messy" identities on Twitter, taking on multiple, only partially professional roles in their social network activities (Budge et al., 2016).

Research dissemination via twitter: moving towards a push model of scientific communication?

Twitter-based indicators have been discussed as an alternative metric for the attention that publications receive, complementing citation-based indicators (Eysenbach, 2011; Mohammadi et al., 2018; Ortega, 2016; Thelwall et al., 2013). However, there are no clear relationships between Twitter usage and academic activity (Ferreira, Mongeon, and Costas 2021). At the same time, researchers' tweets might provide evidence of a profound shift in scholarly communication (Sugimoto et al., 2017) which is an integral aspect of all scientists' work (Côté & Darling, 2018). Put simply, tweets can be actively launched whereas most relevant citations have to be passively waited for (except for self-citations—which are, however, already excluded from many statistics). To date, the dominant mode of research dissemination is the pull-model, in which research is disseminated through publishers, leaving only a passive role for researchers. In turn, those interested in research results have to actively search for new information and "pull" it in from publishers, libraries, or other channels. Conversely, by using social media, researchers can gain agency by connecting with their audience directly and by actively promoting their results, "pushing" them towards their audience. Hence, the increased use of social media and especially Twitter could be read as marking a shift in research dissemination towards a push-model (Allen et al., 2013; Klar et al., 2020).

The mechanism of research dissemination on social media in the push model can be understood as a dissemination pipeline, in which six factors determine the degree of dissemination success (Allen et al., 2013). First, the *reach* of the webpage on which the research content is published limits the impact that research might have in terms of "the number of people given the opportunity to view the web page". Second, *engagement*, referring to "the number of people who view and then 'like' or go on to share the content" determines the impact further. Third, *virality*, i.e. the share of those who engage with the content and write about the research on social media, influences potential impact. Fourth, actual *dissemination* of the research can be expressed by the number of individuals reading the research content. Fifth, *impact* can be defined by "the number of people who change their thinking or practice because of the research". Sixth and last, the research content receives *citations* in the peer-reviewed literature.

However, Allen and colleagues (2013) found that these mechanisms do not necessarily build on each other. Rather, the publication of research on social media in itself already promotes dissemination by increasing webpage views and PDF downloads, irrespective of

whether there is technical evidence of reach, engagement or virality on the Twitter network itself. Arguably, this may be the case since much of the resulting uptake of ideas and dissemination could again occur offline (in face to face conversations about tweets) and/or through traditional, more formal channels (downloading and then the subsequent conventional citation of papers). Accordingly, this paper will analyse selected, relevant foundations for research dissemination via social media, leaving aside indicators for actual dissemination. As nearly three quarters of all scientific Twitter users use the platform for professional purposes (Yu et al., 2019), researchers' Twitter uptake, activity and popularity are relevant objects of study in themselves.

Analysing the case of researcher's Twitter usage in a uniform institutional/organisational setting, we demonstrate that some of the variety and diversity in scientific Twitter usage encountered in existing studies (Yu et al., 2019) can indeed be explained by factors related to individual-level characteristics and activities.

Analytical framework

Our undertaking to study the relationship between research productivity and the Twitter uptake and activity of researchers and their popularity is exploratory in nature. However, prior literature provides guidance and key concepts for the development of our analytical framework.

Twitter is an intensely used social media channel for academic communication (Sugimoto et al., 2017). There are at least two motivations for academic tweeting. On the one hand, new ideas, results, or findings might motivate academic tweets. On the other, attending academic events such as conferences might trigger academic tweets, as such events provide an opportunity to share information and network. Yet, scientific communication is not a primary activity of academic Twitter users, and academics might also use Twitter with other motives, such as to obtain and to share more general information (Ke et al., 2017). Moreover, how researchers use Twitter might relate to their academic discipline, with existing evidence suggesting that while most research tweets come from social scientists and humanities researchers, the share of tweeting researchers is highest in biomedical and health sciences (Costas et al., 2020; Ke et al., 2017; Mohammadi et al., 2018).

Our analysis builds on previous literature in several ways. First, it extends the study of Twitter usage to a relevant region beyond the Anglo-Saxon world on which most existing studies on scientific Twitter usage have so far focused (Costas et al., 2020; Mohammadi et al., 2018). Second, it complements research that relies on convenience samples and contributes to efforts to match bibliometric and Twitter data on a large scale. We have generated a population dataset that includes all the researchers from the Fraunhofer-Gesellschaft, the largest applied research organization in Europe, both those who tweet and those who do not. As this sample covers all researchers employed by this organization, our study overcomes selection issues from which most prior literature suffer. Moreover, this sample allows us to shed light on the patterns of Twitter usage in applied research across different disciplines in the natural sciences and engineering. Third, we complement the established analytical perspective focusing on the relationship between tweets and citations, by turning to the inverse relationship between a researcher's productivity (output of scientific articles), the quality of their output (citations of scientific articles) and their Twitter uptake, activity and popularity. In addition, we consider their inclination to attend conferences and publish proceedings in order to address the above-mentioned opportunity dimension. The core

rationale behind this is to deepen our understanding of "who tweets" in terms of their more general academic profile. If tweets increase the visibility of research, then more productive and more capable researchers should have stronger incentives to tweet. At the same time, this effect may be overriden by the opportunity dimension.

As outlined above, our approach is based on an understanding of social media research dissemination that goes beyond previous literature (Allen et al., 2013). We consider whether the difficulties of prior research in demonstrating the relationships between *reach, engagement* and *virality,* on the one hand, and *citations,* on the other hand, might be due to the conceptualization of the dissemination pipeline as presented above, starting with social media reach while disregarding its relevant foundations in social media *uptake, activity* and *popularity*. Building on Allen et al.'s (2013) finding that impact cannot always be directly explained by the chain of mechanisms in the social media research dissemination pipeline, we deduce that it will be essential to investigate which researchers are more likely to make use of the social media research dissemination pipeline in the first place.

We posit that understanding the factors that lead academics to turn to social media might be just as crucial as understanding the determinants of subsequent dissemination processes. Hence, our analysis will focus on considering social media *uptake* and *activity,* then move on to *popularity* but exclude any subsequent steps which would be difficult to capture in a population analysis anyway. We maintain that we need to establish whether the popularisation of research outputs on social media depends on academic substance or on other factors before analysing whether a push model of research dissemination has emerged, and ask:

RQ 1: How are Twitter uptake, activity and popularity associated with researchers' productivity and/or the quality of the outputs they produce?

By studying these connections between the substance of research results and Twitter engagement, we provide a basis for further studies of the potential emergence of new models of research dissemination.

As an alternative explanation for engaging with Twitter, our review of the literature suggested that academics' use of Twitter might be motivated by events and conferences (Wen et al., 2014; Letierce, Passant, and Decker 2010). To observe whether Twitter provides an additional backchannel for exchanges of ideas and information, we ask:

RQ 2: How is participation in real-world conferences associated with Twitter uptake, activity and popularity on Twitter?

Finally, we consider that the disciplinary affiliations and personal characteristics of individuals will affect all three of these relationships. Before jumping to conclusions, we have to rule out whether the inclination to tweet is broadly circumstantial and idiosyncratic as some extant literature suggests (Yu et al., 2019). It has been widely acknowledged that the *scientific age* of individuals relates to both their academic performance (Gingras et al., 2008; Maflahi & Thelwall, 2021) and their preferences and habits with a view to communication (Bell et al., 2013; Perrin, 2015)—not least as it tends to correlate significantly with their biographical age. What is more, previous literature has emphasized that gender might be negatively associated with the attention received in academic circles for systemic reasons (Klar et al., 2020). Accordingly, patterns of Twitter uptake, usage and popularity might correlate with such biases just as with citations. Hence, we ask:

RQ 3: How are disciplinary affiliation, scientific age and gender associated with all three dimensions of Twitter engagement considered above (uptake, usage and popularity)?

Data and methods

Data

We use a unique *population dataset* generated by identifying the Twitter accounts of all researchers employed by the Fraunhofer-Gesellschaft, the largest organization for applied research in Europe. Fraunhofer employs around 29,000 researchers in more than 70 institutes and research centres in Germany alone. Most research is conducted in the areas of engineering, life sciences and computer science, the main goal being to develop key technologies and facilitate the commercial exploitation of this work by business and industry. Thus, Fraunhofer as a whole plays a central role in the German innovation and research ecosystem.

Honing in on the Twitter usage of applied researchers, we construct a dataset including active researchers employed at the Fraunhofer-Gesellschaft, i.e. researchers having at least one publication listed in *Elsevier's Scopus* database. To identify researchers that are active on Twitter and use their account at least partly for work-related purposes, we use the *rtweet package* for R(Kearney, 2019). As a first step, the search for individual accounts on Twitter was based on matching the internal list of Fraunhofer employees' names with those listed in Twitter accounts. Initial tests based purely on matching researchers' names to those names listed in Twitter accounts resulted however in a large number of false positives which invalidated the sample. Hence, we identified all Fraunhofer institutes or centres ($n = 68$) with a Twitter profile and gathered basic information on all the followers of each institute or centre. Thereby significantly narrowing our search space. If there is a name match as well as a documented relation to Fraunhofer, the likelihood of false positives is practically ruled out as manual checks have confirmed. At the same time, manual validation confirmed that no known Twitter accounts were falsely excluded because of this restriction. As a side effect, reducing our search space to followers of Fraunhofer institutes, we gain additional certainty that a matched employee is using Twitter at least partially for work related purposes—as following one's employer is strongly indicative of work related Twitter usage. All data was downloaded from Twitter in early 2022.

In parallel, we created a dataset of scientific publications—journal articles, letters, reviews, notes and conference proceedings—based on the author-level data for all German authors since 2000. Bibliometric information was sourced from *Elsevier Scopus*, one of the largest bibliometric databases covering the majority of all scientific publications worldwide. Studies have shown that the Scopus database tends to be biased towards natural sciences, engineering and Biomedical research and thus disfavours social sciences and arts & humanities (Mongeon & Paul-Hus, 2016; Vera-Baceta et al., 2019). However, in the case of the Fraunhofer-Gesellschaft this bias is less relevant. The data were retrieved using the Scopus 2019 version. Here, we also included the information as to whether an author is an employee of the Fraunhofer-Gesellschaft based on the affiliation information in the respective publications. An author was counted as a Fraunhofer employee if he or she had at least one publication with a Fraunhofer affiliation.

In the next step, the two databases, i.e. the authors of scientific papers as well as the active Twitter users, were connected with the help of a string matching algorithm at the level of author-names based on the Levenshtein distance, which counts the number of edits in order to align two text strings. For this purpose, all text data was cleaned beforehand, i.e. all characters were set to lower case, and punctuation and special characters were removed.

To exclude homonyms from the data, the string matching of a person's name was performed following four steps. (i) All matches with a similarity score of 1 were included (exact match); (ii) matches with a similarity score between 0.9 and 1 were included after manual validation; (iii) all matches were validated based on affiliation information (internal employee list vs researcher identified via Scopus); (iv) out of all matches, a random generated subset of the data was validated manually (with a focus on systemic biases).

Measures

On the basis of the dataset described above, we generated a set of five dependent variables for our regression models. The first one is the information as to whether an author is actually active on Twitter. This was operationalized by the number of followers, i.e. an author was coded as being a Twitter user once he or she had at least one follower. Second, we use as dependent variables the number of tweets and retweets that a user has posted, and the number of accounts that a user follows. With both these variables, we seek to measure a user's Twitter activity. Third, we use the actual number of followers, and the number of public lists that a user is a member of as dependent variables. Twitter users can create lists of accounts to display the tweets from this list, and also follow a list rather than a specific account. With these two variables, we measure the popularity of Twitter users.[1]

The main explanatory variables in our models are the stock of scientific publications under the following categories: article, letter or review by an author as we consider that more productive researchers who publish larger numbers of scientific articles have a stronger motivation to use Twitter and spark more interest from other users. Furthermore, we consider the average number of citations to an author's scientific articles to consider not only the sheer volume, but also the quality of the scientific output on which Twitter activity could depend. Following the same logic, we also include the average impact factor of the journals in which an author has been published.

In a similar fashion, we count the number of conference proceedings published by an author. As stated in earlier literature, we expect that there are field specific preferences in publishing conference proceedings, e.g. informatics and engineering than in other fields (which does not necessarily imply that standard publications play a lesser role in absolute terms). We consider conference proceedings separately as they have a much stronger direct association with the opportunity for tweeting as discussed in the conceptual section and are usually subject to far less stringent quality controls than traditional articles. Along similar lines, we include a count of the number of conferences an author has attended. This information comes from Microsoft Academic Graph (MAG), and was matched to our dataset at the author name level.

We add a dummy variable for female gender as gender may—empirically—play a role in deciding the popularity of researchers (Zhu et al., 2019). To account for seniority, we include the scientific age i.e. the numerical difference between the year 2020 and the year of an author's first publication in the Scopus database. Finally, we consider disciplinary affiliations, using dummy variables indicating the most frequently mentioned All Science Journal Classification (ASJC) code for a researcher in Scopus. We do so because previous research has shown that Twitter usage might vary according to discipline. For

[1] This is not synonymous with attention, i.e. the number of views that a user receives, since which users see which tweets is also determined by Twitter's algorithms and content moderation.

Table 1 Descriptive statistics

Variable	Min	Pctl. 25	Median	Pctl. 75	Max	Mean
twitter_yes (d)	0	0	0	0	1	0.05
followers	0	0	0	0	27717	18.78
users_followed	0	0	0	0	10312	23.23
listed_count	0	0	0	0	673	0.69
statuses_count	0	0	0	0	455511	109.12
favourites_count	0	0	0	0	168130	119.33
pub_ar	0	0	1	3	346	3.98
pub_cp	0	0	1	4	352	4.25
cit_article	0	0	1	11	6883	24.15
no_of_conf_visits	0	0	0	0	107	0.62
avg_jif	0	0	1.31	3.07	25.92	1.83
scientific_age	2	5	8	13	29	9.67
Female (d)	0	0	0	0	1	0.17
engineering_yes (d)	0	0	0	1	1	0.26
computersc_yes (d)	0	0	0	0	1	0.15
materialssc_yes (d)	0	0	0	0	1	0.14
physics_yes (d)	0	0	0	0	1	0.19

d dummy variable

a parsimonious approach, we include dummy variables only for the four academic disciplines most prevalent at Fraunhofer: Computer science, materials science, physics, and engineering (the distribution of academic disciplines at Fraunhofer is skewed towards these disciplines).

Estimation approach

Main Models. We use two kinds of regression models in our analyses. To consider the relationship between Twitter as a binary response variable and our explanatory variables we use logistic regressions. To consider the relationship between our explanatory variables and Twitter activity and popularity, we resort to negative binomial regression We do so as our response variables measuring Twitter popularity are count variables and our sample contains many researchers who do not use Twitter, i.e. our count variable is zero-inflated, which is taken into account by negative binomial models.

Robustness checks. We repeat the estimation of our main models, this time with dummy variables considering all disciplines following the ASJC taxonomy, rather than only the four disciplines most prevalent at Fraunhofer.

Results

Table 1 presents the descriptive statistics. For the dummy variables included in the model, the mean value indicates the share of observations where the dummy takes the value of 1. Around 5% of the 15,609 individuals included in our dataset are on Twitter ($n = 842$).

Table 2 Pairwise correlations (Spearman)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1) twitter_yes (d)															
(2) followers	0.96														
(3) users_followed	1	0.96													
(4) listed_count	0.68	0.72	0.69												
(5) statuses_count	0.89	0.91	0.9	0.74											
(6) pub_ar	0.01	0.01	0.01	0	0										
(7) pub_cp	0.09	0.08	0.09	0.06	0.08	0.08									
(8) cit_article	0.01	0.01	0.01	0.01	0	0.85	0.08								
(9) no_of_conf_visits	0.13	0.12	0.13	0.1	0.12	0.01	0.41	0.01							
(10) avg_jif	− 0.01	− 0.01	− 0.01	− 0.02	− 0.01	0.77	− 0.11	0.8	− 0.05						
(11) scientific_age	0.02	0.02	0.02	0.01	0.02	0.42	0.35	0.39	0.15	0.21					
(12) female	− 0.03	− 0.03	− 0.03	− 0.02	− 0.03	0.05	− 0.19	0.07	− 0.07	0.12	− 0.11				
(13) engineering_yes (d)	− 0.01	− 0.02	− 0.01	− 0.02	− 0.02	− 0.06	0.18	− 0.11	0.05	− 0.14	0	− 0.1			
(14) computersc_yes (d)	0.13	0.12	0.13	0.11	0.13	− 0.19	0.29	− 0.16	0.36	− 0.2	0.06	− 0.05	− 0.24		
(15) materialssc_yes (d)	− 0.05	− 0.04	− 0.05	− 0.03	− 0.04	0.15	− 0.07	0.12	− 0.1	0.12	0.02	0.01	− 0.24	− 0.17	
(16) physics_yes (d)	− 0.04	− 0.04	− 0.04	− 0.04	− 0.04	− 0.04	− 0.01	− 0.02	− 0.12	0.01	− 0.02	− 0.06	− 0.29	− 0.2	− 0.19

d dummy variable

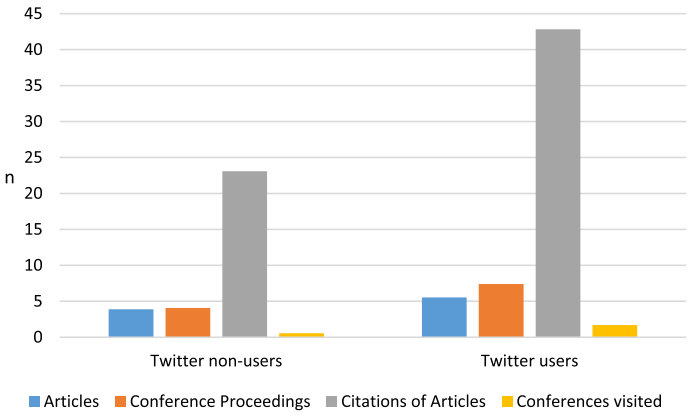

Fig. 1 Difference between Twitter users and non-users, all disciplines

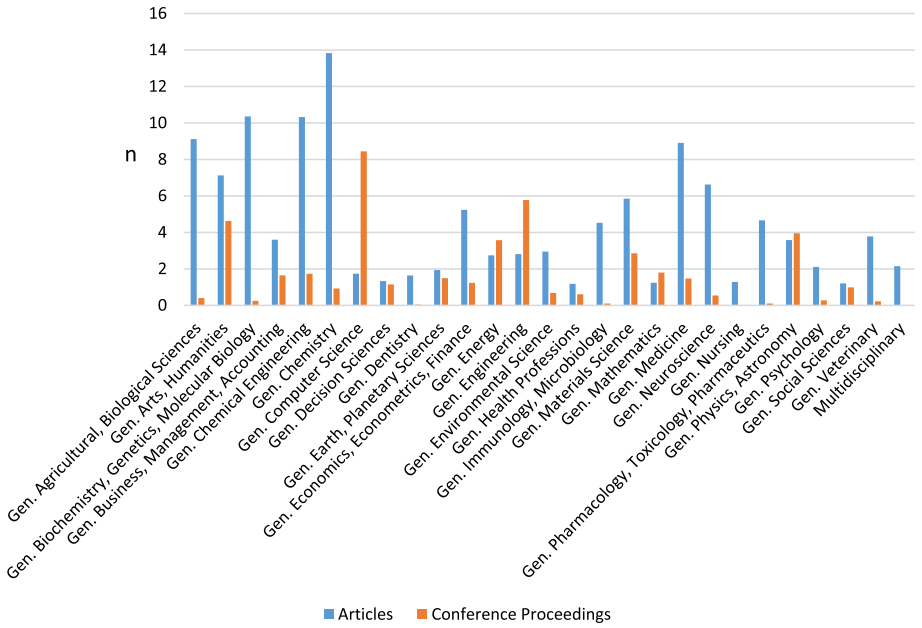

Fig. 2 Average publications per discipline by Type

Table 2 presents the Spearman correlation of our variables. Spearman correlations describe the linear correlations between the rank values of variable pairs and provide a clearer perspective on the correlations between zero-inflated variables such as our measures of Twitter uptake, activity and popularity (Pimentel, 2009). Our five Twitter-related dependent variables are highly correlated, at least partly because our Twitter variables have the value of 0 for most individuals in our sample.

Figure 1 provides initial descriptive evidence of the differences between individuals that have taken up Twitter and those who have not. Researchers using Twitter display a higher

Table 3 Main results

Variables	Twitter uptake	Twitter activity		Twitter popularity	
	(1)	(2)	(3)	(4)	(5)
	twitter_yes	statuses_count	users_followed	listed_count	followers
pub_ar	0.00573*	− 0.00414	0.00561	− 0.0258	− 0.0251
	(0.00325)	(0.0170)	(0.0225)	(0.0219)	(0.0179)
pub_cp	0.00334	− 0.00669	0.00940	0.00578	0.0173
	(0.00235)	(0.0109)	(0.0145)	(0.0115)	(0.0137)
cit_article	0.000259	0.00138	0.00181	0.00298	0.00504*
	(0.000240)	(0.00242)	(0.00250)	(0.00236)	(0.00263)
no_of_conf_visits	0.0275***	0.0230	0.111	0.197**	0.172**
	(0.00822)	(0.0517)	(0.0712)	(0.0790)	(0.0820)
avg_jif	0.0126	0.0678	− 0.0248	− 0.0586	− 0.0659
	(0.0186)	(0.0723)	(0.0439)	(0.0602)	(0.0502)
scientific_age	− 0.00580	− 0.0370	− 0.0449**	− 0.0281	− 0.0306
	(0.00652)	(0.0233)	(0.0196)	(0.0232)	(0.0216)
female	− 0.359***	− 2.209***	− 1.148***	− 1.401***	− 1.354***
	(0.112)	(0.354)	(0.283)	(0.319)	(0.296)
computersc_yes	0.902***	0.764*	0.486	0.359	0.201
	(0.106)	(0.449)	(0.347)	(0.395)	(0.362)
materialssc_yes	− 0.634***	− 0.285	− 0.00908	− 0.164	0.271
	(0.150)	(0.436)	(0.324)	(0.406)	(0.346)
physics_yes	− 0.455***	1.148***	− 0.272	− 0.252	− 0.540*
	(0.128)	(0.375)	(0.303)	(0.350)	(0.316)
engineering_yes	− 0.0467	0.408	− 0.175	− 0.717**	− 0.677**
	(0.107)	(0.365)	(0.287)	(0.330)	(0.308)
Constant	− 2.920***	4.408***	3.418***	0.0466	3.306***
	(0.0971)	(0.329)	(0.253)	(0.291)	(0.259)
Observations	15,609	15,609	15,609	15,609	15,609

Standard errors in parentheses. ***$p<0.01$, **$p<0.05$, *$p<0.1$

level of activity on all accounts: They publish more articles and conference papers, receive more citations, and attend more conferences. Figure 2 plots the average number of publications per researcher by discipline, distinguishing between the category of articles (comprising articles, letters, reviews) on the one hand and conference proceedings on the other. Clearly, the share of conference proceedings is unevenly distributed. Focusing on the four dominant disciplines at Fraunhofer-Gesellschaft, conference proceedings are the dominant mode of publishing in Computer Science and in Engineering and make up roughly half of the publications in General Physics and Astronomy. In General Materials Science as in most other disciplines, publishing articles is more common than publishing conference proceedings.

Table 3 presents the main models. The logistic regression Model 1 focuses on Twitter uptake, demonstrating that scientific quality as measured by the stock of citations does not significantly determine whether scientists have ever used this new means of communication or not. In contrast, scientific productivity measured by the overall stock of publications,

and the number of conference visits are positively and significantly associated with Twitter uptake. Moreover, we find that Twitter uptake is determined by gender as well as by disciplinary affiliation. Ceteris paribus, female authors are less likely to use Twitter. Computer scientists are more likely to use Twitter, whereas material scientists and physicists are less likely to use Twitter than scientists from other disciplines.

The negative binomial regressions in Model 2 and Model 3 consider Twitter activity with regard to sharing and sourcing information, this is measured by the number of tweets and retweets on the one hand and the number of accounts that a user follows on the other. Both these models yield far less specific results. According to both models, female authors are less active on Twitter and a higher scientific age is associated with lower numbers of accounts followed. Computer scientists and physicists turn out to be above average active on Twitter in terms of their tweets and retweets. These points resonate with the above findings on Twitter uptake and seem to confirm the model's overall validity and pertinence. No further significant correlations can be identified with scientific output or the quality or "occasions to tweet" as reflected in conference visits.

The negative binomial regression models 4 and 5 focus on Twitter popularity as measured by the number of public lists that a user is on and the number of users that an account is followed by yield more specific results. Both personal traits and disciplinary affiliation matter. In both models, the number of conference visits is positively associated with Twitter popularity while the overall stock of scientific articles is not. Female gender is negatively associated with Twitter popularity. Moreover, individuals with more citations tend to have more followers whereas tweeting physicists and engineers have fewer followers than scientists from other disciplines. Engineers also appear on fewer public lists than their colleagues from other disciplines.

As a robustness check, Table 4 presents the main models, this time including variables for all scientific disciplines. These models confirm most significant associations found in the main models and thereby confirming our results. They reveal stronger positive and significant associations between scientific productivity and Twitter uptake than our main models. They also reveal stronger positive associations between Twitter popularity and scientific quality as measured by the citations received, which turns out significant for both the number of public lists and followers.

Discussion

Regarding our research question '*how are Twitter uptake, activity and popularity associated with researchers' productivity and/or the quality of the outputs they produce?'* we find that publication output is positively associated with Twitter uptake both in our main models and our robustness checks. Hence, research productivity and Twitter uptake as a fundamental prerequisite for research dissemination through social media are linked in the population under study. However, the number of conference visits proves to be at least as significant a predictor, indicating that Twitter uptake is linked to opportunities and occasions to tweet at social events as well, where formal and informal knowledge exchanges take place. Concerning Twitter activity, the rather non-specific results of our analysis resonate with some authors' claims that scientists, like other citizens, use Twitter for all sorts of purposes, often unrelated to their professional activity (Robinson-Garcia et al., 2017), and that the number of tweets as such is unfit to assess scientific dissemination (Yu et al., 2019). Furthermore, these results can be read as indicating that those accessing science via

Table 4 Robustness Checks (Same models as above, but with dummies for all disciplines)

Variables	Twitter uptake	Twitter activity		Twitter popularity	
	(1)	(2)	(3)	(1)	(2)
	twitter_yes	statuses_count	users_followed	listed_count	followers
pub_ar	0.00724**	0.00328	0.0128	− 0.000214	− 0.0200
	(0.00331)	(0.0241)	(0.0258)	(0.0250)	(0.0211)
pub_cp	0.00257	− 0.0133	0.00963	− 0.00641	0.0129
	(0.00238)	(0.0112)	(0.0157)	(0.0120)	(0.0140)
cit_article	0.000219	0.00336	0.00222	0.00552**	0.00677**
	(0.000244)	(0.00284)	(0.00281)	(0.00279)	(0.00274)
no_of_conf_visits	0.0273***	0.0295	0.101	0.154**	0.164**
	(0.00821)	(0.0516)	(0.0698)	(0.0782)	(0.0821)
avg_jif	0.0220	0.0257	− 0.0384	− 0.0534	− 0.0754
	(0.0191)	(0.0767)	(0.0486)	(0.0650)	(0.0530)
scientific_age	− 0.00481	− 0.0284	− 0.0472**	− 0.0220	− 0.0242
	(0.00658)	(0.0246)	(0.0200)	(0.0234)	(0.0217)
female	− 0.366***	− 2.117***	− 1.138***	− 1.281***	− 1.248***
	(0.114)	(0.383)	(0.302)	(0.346)	(0.326)
computersc_yes	0.440	2.867	0.892	2.569	2.410
	(0.525)	(1.988)	(1.609)	(1.828)	(1.654)
materialssc_yes	− 1.124**	1.758	0.371	1.743	2.385
	(0.536)	(1.999)	(1.605)	(1.827)	(1.654)
physics_yes	− 0.933*	3.339*	0.111	1.915	1.681
	(0.530)	(1.977)	(1.598)	(1.815)	(1.643)
engineering_yes	− 0.516	2.508	0.219	1.459	1.527
	(0.525)	(1.967)	(1.595)	(1.815)	(1.643)
Remaining ASCJ field codes (general level)	INCLUDED	INCLUDED	INCLUDED	INCLUDED	INCLUDED
Constant	− 2.469***	2.259	3.041*	− 2.163	4.995***
	(0.523)	(1.954)	(1.587)	(1.806)	(1.628)
Observations	15,493	15,609	15,609	15,609	15,609

Standard errors in parentheses. ***$p<0.01$, **$p<0.05$, *$p<0.1$

(1) For Model 1, 116 publications were removed from the sample since they belong to ASCJ fields which are hardly represented at Fraunhofer and no Fraunhofer researchers active in these fields use Twitter: Arts and Humanities (8), Immunology and Microbiology (99), Veterinary (9). (2) Together, the dummies in these models for computer science, material science, physics and engineering and remaining ASCJ field codes cover all fields of the ASCJ classification scheme present in the data

Twitter may not necessarily be highly productive researchers, but rather junior scientists who have so far hardly published at all themselves. These results might also underscore that scientist's social media use is mechanical rather than serving the promotion of original thoughts (Robinson-Garcia et al., 2017). Regarding Twitter popularity, we find that citations are a marginally significant predictor in our main models and are clearly significant in our robustness checks. Moreover, conference visits are positively associated with both our measures of popularity. The discrepancy between the unspecific results from the models on Twitter activity and our clear findings on popularity further suggests that while the pushing

out of scientific information out via Twitter may be indeed indiscriminate (Yu et al., 2019), users seem to use the network as a tool to purposefully follow relevant sources. It appears that, Twitter users have an interest in following researchers who tweet high quality research and are more visible at conferences. This points to traditional pull mentalities transferred to a new platform rather than a profound transformation of research dissemination in the form of a "push-model".

Regarding our second research question *'how is participation in real world conferences associated with Twitter uptake, activity and popularity on Twitter?',* clear correlations between Twitter activity and conference attendance or the publication of conference proceedings stand out. This is consistent with the suggestion in prior literature that researchers use of social media is largely due to the opportunity and occasion provided by conference participation (Ke et al., 2017). More generally, this can be taken as an indication that researchers who are active communicators in the "real-world domain", i.e. at conferences, also tend to be more active communicators on social media. Potentially, some researchers have always displayed a propensity to communicate more in line with a "push model", even before the advent of social media. It is likely that such active promoter of their findings are more likely to take advantage of the "opportunity and occasion to tweet" that conferences provide, as described in the existing literature.

Regarding our third research question, '*how are disciplinary affiliation, scientific age and gender associated with all three dimensions of Twitter engagement considered above (uptake, usage and popularity)?',* one could argue that it doesn't come as a surprise that male scientists are more inclined to communicate intensely through social media channels (Klar et al., 2020), even if a detailed interpretation of this fact would require more in-depth and bespoke analyses. It is noteworthy that age has no influence on Twitter uptake—which can be interpreted as an expression of Twitter's ever more prevalent role in science, which even more senior, less tech savvy colleagues find increasingly difficult to entirely dismiss. However, older researchers are indeed less active on Twitter which might indicate that they are less adept at using Twitter or use it less frequently. Nonetheless, they have a popularity similar to younger researchers which may indicate that the information (potentially) offered on an account is at least as relevant for its popularity as the user's activity. Regarding disciplinary affiliation, our main models show that computer science provides a particularly fertile environment for social media usage, but our robustness checks do not support this. Hence, it remains open whether researchers in this discipline are indeed significantly more inclined to communicate more on social networks.

The volume of applied researchers' scientific output is positively associated with their Twitter uptake, but not with their activity and popularity on Twitter—or at least not yet. In contrast, the quality of research as measured by citations is related to Twitter popularity, but not to Twitter uptake or activity. Moreover, we find that real-world occasions and triggers for communication, as measured by the number of conference visits or conference proceedings, provide important explanatory elements as they are associated with Twitter uptake and popularity. Twitter activity, however appears to be largely unrelated to bibliometric indicators and conference visits, and—gauging from the few indications that our models deliver—more dependent on personal characteristics. In line with the ambivalent findings and suggestions from previous literature (Allen et al., 2013; Robinson-Garcia et al., 2017) we find that whether and how applied researchers take up, are active on, and have a high popularity on Twitter also depends on personal traits like age and gender and on the specific disciplinary environment.

Overall, our findings provide at best limited evidence of a shift from the conventional pull model of academic communication to a push model, as suggested by Klar and

colleagues (2020). Our Twitter-based indicators are associated with a mix of bibliometric indicators, conference visits, individual traits and disciplinary affiliation. As bibliometric indicators and conference visits are positively associated with Twitter uptake and popularity, our analysis suggest important links between individual's research outputs, occasions and opportunities for scientific tweets, and patterns in their Twitter usage. Furthermore, our results suggest that a better understanding Twitter activity may also require exploration of alternative explanations to those pursued in this study.

Conclusion

Our paper uses population data from the largest organization for applied research in Europe in order to study twitter uptake, activity and popularity among researchers of different academic disciplines. It examines whether research productivity as measured by publication output, conference visits and citations affects the probability of researchers taking up Twitter use, being active on Twitter, and increasing their popularity. It adds to the literature of social media research dissemination by showing that Twitter usage in applied research is best understood as contributing to and driven by both push and pull mechanisms of research dissemination. Moreover, this paper complements the existing literature by illuminating Twitter usage of researchers beyond the Anglo-Saxon world. What is more, we have presented an innovative methodology to derive and analyse a unique population dataset combining data on twitter activity and bibliometric information on Fraunhofer researchers, thereby complementing recent contributions on automated approaches for generating large datasets and tweeting researchers (Costas et al., 2020).

Our analysis shows that the use of Twitter as a vehicle for academic communication in German applied research is in its infancy as shown by the small share of researchers who have taken up Twitter so far. Our findings suggest that Twitter uptake, activity and popularity are associated with a mix of variables from bibliometric indicators, conference attendance, individual characteristics and the disciplinary environment. With regard to the emergence of a push model of research dissemination, they provide mixed evidence.

Both Twitter uptake and popularity correlate with academic substance and occasions to tweet arising from the participation in academic conferences. This provides some evidence for researchers actively pushing their research, as research output is positively associated with Twitter uptake. On the other hand, research quality as measured by citations and conference visits are positively associated with popularity. Hence, Twitter users seek to pull in relevant research results because they tend to follow researchers who produce research of high quality and are more visible at conferences.

In summary, rather than a competition between different models of research dissemination, we observe both push and pull mechanisms of research dissemination at play. Moreover, such a mix of factors is not restricted to the realm of social media. The relation of conference attendances to push or pull mechanisms of dissemination is not straightforward. Researchers might attend conference both to promote their work and to learn about the activities of their peers. This parallel reflects that social media, just like scientific conferences, facilitates complex interactions and exchanges of information rather than a monodirectional dissemination pipeline.

Measures addressing researchers' Twitter activity, as opposed to Twitter uptake or popularity, are unrelated to both bibliometric indicators and conference attendances. This resonates with previous findings that only a fraction of researchers' Twitter activity actually

pertains to research (Mohammadi et al., 2018), suggesting that the sheer extent of Twitter activities may not primarily result from a researcher's visibility or relevance. Thus, our findings corroborate that further investigations into the motives of researchers for using Twitter could be key to understanding how social media relates to research work, and that additional explanatory variables are needed to better understand how social media relates to research work. Among others, the robust and significant negative associations between female gender and Twitter-based metrics deserve further attention in future inquiry.

With regard to the remaining limitations, it might be relevant to explore similar patterns for corresponding activities in either universities, universities of applied science or public research organizations other than Fraunhofer that cover a broader range of disciplines. Moreover, comparative studies on data from other countries might help to establish relevant international comparisons. In terms of method, more and more valid indicators could be developed for traditional activities at conferences that help to overcome the disciplinary biases of the established indicators. Likewise, comparative analysis conducted across other social media channels whose function, purpose and business model differ from that of Twitter could help to complement our picture of patterned variation in academic social media use.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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