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Building Buzz: (Scientists) Communicating Science in New Media Environments

Xuan Liang[1], Leona Yi-Fan Su[1], Sara K. Yeo[2], Dietram A. Scheufele[1], Dominique Brossard[1], Michael Xenos[1], Paul Nealey[3], and Elizabeth A. Corley[4]

Abstract

Public communication about science faces novel challenges, including the increasing complexity of research areas and the erosion of traditional journalistic infrastructures. Although scientists have traditionally been reluctant to engage in public communication at the expense of focusing on academic productivity, our survey of highly cited U.S. nano-scientists, paired with data on their social media use, shows that public communication, such as interactions with reporters and being mentioned on Twitter, can contribute to a scholar's scientific impact. Most importantly, being mentioned on Twitter amplifies the effect of interactions with journalists and other non-scientists on the scholar's scientific impact.

Keywords

media and society, communication effects, science communication, social media

For many researchers, communicating with the public about research results rarely entails more than a press release through their institution's public relations division, and possibly a follow-up interview with a journalist. Only a minority of scientists have been actively engaged in communicating science through popular media outlets. Among them are prominent and highly visible researchers, such as Carl Sagan, Richard

[1]University of Wisconsin-Madison, Madison, WI, USA
[2]University of Utah, Salt Lake City, UT, USA
[3]University of Chicago, Chicago, IL, USA
[4]Arizona State University, Phoenix, AZ, USA

Corresponding Author:
Dietram A. Scheufele, Department of Life Sciences Communication, University of Wisconsin-Madison, 309 Hiram Smith Hall, 1545 Observatory Drive Madison, WI 53706, USA.
Email: scheufele@wisc.edu

Smalley, and Neil deGrasse Tyson. In spite of these visible exceptions, there continues to be a normative assumption among scientists that public communication is not valuable or is even detrimental to their academic careers.[1] Most believe scientists are expected to be modest and dedicated to their research, rather than trumpeting their work in popular media.[2] The rewards for communicating science through traditional media are thus believed to compromise a scientist's integrity and authority.[3] In fact, the term *Sagan-ization* is often used to describe scientists who "become popular enough as an explainer of science to risk the contempt of more 'serious' researchers."[4] This is a reference to the widely held notion that the popular Cornell astrophysicist, Carl Sagan, was denied admittance to the National Academy of Sciences because of his publicly televised series, *Cosmos*.[5]

Historically, changing socio-cultural patterns and an evolving communication environment have led to renewed attention to scientists' roles in communicating science outside the ivory tower. The increasing demand for science and technology during World War I put scientists in the public eye more than ever before. Many scientists since then have been under the impression that nationally funded science in the United States could be supported "only if the scientific and nonscientific sectors of American culture were united."[6] This desire for public acceptance of scientific research, especially with respect to emerging technologies with significant social and ethical implications, inspires a "legitimation discourse" of science in media outlets.[7] Scientific institutions, as well as some scientists, increasingly orient themselves toward the media. Simultaneously, media are increasingly attentive to scientific research.[8] Major scientific institutions and funding agencies also require public communication of science and technology (PCST) components in their funded research.[9]

The Internet has fundamentally changed our modern media environment and audiences' media consumption habits.[10] The volume of content about science and technology in traditional news outlets has ebbed due to significant declines in readership and subscriptions. In turn, these declines have forced media corporations to decrease the number of journalists who specialize in communicating scientific issues.[11] In 1989, there were ninety-five weekly science sections in newspapers in the United States. However, by 2005, fewer than a third of these remained, and that number plunged to nineteen in 2012.[12] In light of these changes, the boundaries of communication that exist between scientists, journalists, and public audiences become more blurred. The public relies on various media across both traditional and online platforms for science news and information,[13] and almost half of the public turns to online sources to follow developments in scientific fields.[14] This poses new opportunities for scientists to play an active role in communicating directly with various publics.

However, the question still remains whether public communication efforts by scientists yield any rewards. Researchers have yet to investigate empirically and agree on the impact of communicating one's work in various media, particularly online media, on scholars' advancement within the ivory tower. Our study fills this gap in the literature by exploring whether public outreach via traditional and online media can boost scholars' academic careers. Specifically, we attempt to address whether new media can amplify the effect of traditional public outreach on scholars' scientific impact.[15]

Scientific Impact

Science is a collective endeavor. The impact of scientific research is defined as the extent to which it can benefit other researchers in generating further discoveries,[16] and the cumulative impact of a particular researcher's scientific output, such as publications, adds up to the researcher's "scientific impact."[17] Because scientific publications play a central role in systematically documenting research findings and facilitating information exchange between researchers, citation analysis is widely acknowledged as a powerful method for quantifying researchers' scientific impact in order to evaluate and compare scholars in hiring, funding, and tenure decisions.[18] Although scientists may alternatively refer to scholars' "scientific reputation" (opinions generally held by peers about a scholar), the multi-dimensional nature of this notion generates a mix of explicit (e.g., bibliometric indicators) and nebulous measures (e.g., certain valued qualities such as fair play, integrity, honesty, caring, etc.)[19] that can be affected by subjectivity and bias.[20] In order to utilize fair, transparent, and quantitative approaches to research evaluation,[21] our study focuses on measuring scientific impact instead of scientific reputation.

The h-index, proposed by Hirsch,[22] is a bibliometric indicator that quantifies the scientific impact of a given researcher and embodies a figure of merit.[23] According to Hirsch, a researcher has "index h if h of his or her Np papers have at least h citations each and the other $(Np - h)$ papers have $\leq h$ citations each,"[24] so that a high value in h-index indicates a high scientific impact of the researcher. The convergent validity of the h-index has been confirmed in different research fields[25] and is robust against small errors and single peaks (top-cited papers) in the publication list of a researcher.[26] Although the h-index is sensitive to many factors and should be used with caution,[27] it has been widely accepted in the scientific community[28] due to its accessibility in citation databases (e.g., Thomson Reuters Web of Science) and its advantages over other bibliometric measures, such as total citation count, citations per paper, and total paper count.[29]

Scientific Impact Meets Public "Buzz"

In academia, articles that receive more attention from other scholars in terms of citations are generally considered more important and prestigious, and the relative importance of the other articles that cite it also determines its impact. This idea of scientific impact, a type of "academic buzz," is not unique to scholarly work. For example, the algorithm used by the online search engine Google, PageRank, was originally based on this concept.[30] PageRank positions webpages referenced by many other popular sites as more important, and thus higher in the results of a search. In this sense, the algorithm that calculates a webpage's importance is based on the same logic that evaluates peer-reviewed articles' importance and scholars' academic impact, but on a much larger scale.

Scientists' Interactions with Mass Media and Lay Publics

As science journalism has shifted from traditional to online media platforms, scientists are interacting with reporters more frequently and seamlessly.[31] Science journalists increasingly quote peer-reviewed articles in their stories as a way to gain credibility and readers' trust.[32] Frequent interactions with reporters can increase the visibility and popularity of a scientist and his or her work, as they are more likely to be referenced in journalistic narratives. Such narratives can boost the information transmission from scientific literature to the scientific community and, further, to the general public, while gaining more citations by fellow scholars.[33] On the individual level, scholars who have frequent media contact tend to be more academically active.[34] Yet, contrary to the above findings, the perception of "Sagan-ization" is still prevalent in academia. While it seems reasonable to assume that concordant relationships between scientists and journalists could translate into greater impacts within academia for researchers, the possibility of critical reactions from peers may weaken the potential rewards of such interactions.[35] Due to a paucity of empirical evidence exploring whether interactions with journalists impact scholars' careers, we propose the following research question:

> **RQ1:** With other factors held constant, do scientists' interactions with reporters affect scientific impact?

In addition to media interactions, scientists' efforts to engage lay publics and popularize their research can be wide-ranging, and may include public speeches, school presentations, and collaborations with other non-academic associations. Contrary to the perception of "Sagan-ization," scientists who are active in disseminating their work to lay audiences also perform better than average academically. A study of French scientists, for example, showed that scientists who engaged in more dissemination activities for non-specialized audiences published more peer-reviewed articles and were cited more times per year over their research career than the less engaged scientists.[36] Given that the existing data demonstrate a positive relationship between outreach activities and academic performance in terms of scientific impact, we put forth the following hypothesis:

> **H1:** With other factors held constant, scientists' interactions with non-scientists are positively related to scientific impact.

Science Blogging

Blogs are a Web 2.0-type tool that have increasingly become a source for the public to get information about scientific developments[37] and an open space for scientists from different disciplines to exchange knowledge and evaluate other scientific research.[38] Currently, over 26,000 blog entries have been posted about peer-reviewed research on various science subjects on the Research Blogging platform (http://www.researchblogging.org).[39] As opposed to scientists who publicize their work by talking with journalists, scientists who blog about their research have more individual autonomy over how their scientific developments are communicated to the public. Scientists may blog to circumvent traditional media outlets to highlight their own recently published work and communicate with peers.[40] Some scientists also rely on scientific blogs to survey their academic environments.[41] In addition, scientific blogs may bring issues that are not yet popularized to the attention of the mainstream media.[42] Consistently and regularly updating a blog with scientific achievements may, therefore, help scientists increase the visibility of their published research, including among their peers.

In addition to being an open marketplace for scientific exchange, online communication tools, such as blogs, allow researchers to expand their professional networks through online activities. Evidence suggests that scholars who connect through online environments, including blogs, also collaborate on projects offline.[43] Although studies on scientists' online behaviors are relatively few, those that exist provide support for a positive association between blogging and popularity of a scientist's research. On the basis of this reasoning, we put forth the following hypothesis:

> **H2:** With other factors held constant, scientists' blogging about science is positively related to scientific impact.

Twitter Activity

Twitter is the United States' second largest social networking platform, with 16% of all Internet users having Twitter accounts.[44] The platform provides unique opportunities for scientists to post "tweets," user-generated content with a limit of 140 words, and offers "various degrees of social presence/media richness."[45] In contrast to other online social networking sites (such as Facebook) that control information sharing only with approved "friends," public Twitter posts allow live dialogues visible to anyone unless the user opts to use a private setting. Given the sheer size of Twitter users, the open access, and the relative ease of composing tweets, information shared on Twitter by certain opinion leaders, including some prestigious science writers, can immediately reach a large number of audiences. For example, every tweet from Carl Zimmer may be seen by over 146,000 followers and potentially greater audiences when the post is retweeted by these followers.

In a survey of higher education professionals, researchers found academic use of Twitter has increased among scholars, with 35.2% of surveyed college faculty members using Twitter in 2010, compared with only 30.7% in 2009.[46] In particular, scholars on Twitter were found to be discussing academic conferences and articles.[47] Such discussions on Twitter are often legitimate, interactive, wide-ranging, and cross-disciplinary conversations that are reflective of academic impact.[48] Being cited or mentioned on Twitter could be a new sign of one's academic impact.[49] Eysenbach mined tweets that mentioned published articles in a medical journal (i.e., tweets with reference to the title and URL of journal articles) and found that journal articles mentioned on Twitter were more likely to be frequently cited by other scholars.[50] The current study takes a similar approach to examining mentions of scientists' research on Twitter, which are measured as tweets that include scientists' names and their research with links to information on other websites. On the basis of previous findings, we presume that if scientists are mentioned on Twitter, their research may be more visible, which influences the underlying impact of their work:

H3: With other factors held constant, being mentioned on Twitter is positively related to scientific impact.

Building Buzz in New Media Environments

Contemporary media environments have important implications on how scientists monitor scientific developments and communicate about their research. For example, American neuroscientists now rely on an array of cross-media channels, including traditional journalistic outlets (e.g., newspapers, magazines, radio, and television), new media (e.g., blogs), and interpersonal social networks to keep abreast of new research.[51] In addition, scientists' traditional forms of public outreach, usually interacting with journalists who cover their research in the mass media, can be further disseminated through Web 2.0-type tools. Therefore, in addition to traditional communication efforts undertaken by researchers, it is reasonable to assume that the use of multiple online channels can amplify the effect of other forms of outreach on researchers' scientific impact. On the other hand, if there is a "Sagan-ization" effect, some scholars may argue that scientists who are too engaged (e.g., tweet too often) will suppress the impact of other forms of outreach (e.g., interactions with reporters). Researchers have yet to provide empirical evidence that such interactions between various forms of outreach exist. We therefore put forth the following research question:

RQ2: Do different forms of communication behaviors (i.e., interactions with journalists or other non-scientists, science blogging, and being mentioned on Twitter) moderate each other's effect on scientific impact?

Methods

Sample

Our sample consists of only the most highly cited U.S. scientists within the field of nanotechnology. Nanotechnology is an emerging and complex field that encompasses a broad area of expertise, drawing from the fields of chemistry, materials science, physics, engineering, biology, and others. Its inventions are integrated with modern biology, the digital revolution, and cognitive sciences.[52] We focus on nano-scientists for two reasons. One, elite experts in one discipline may not have an equivalent status in another discipline. By focusing on scientists working in this multidisciplinary field, we can remove the effects of name recognition, which otherwise can be a confounding factor that influences citation patterns and h-indices. Two, the multidisciplinary nature of nanotechnology makes nano-scientists especially pertinent and representative of scientists who work in an evolving scientific community in which the distinctions between disciplines are blurring and research endeavors require interdependence among disciplines.

We sampled authors of the most cited publications indexed in the Thomson Reuters Web of Science database in 2008 and 2009 in order to minimize the potential confounding effects of seniority on the *h*-index.[53] In order to rigorously establish which publications were actually within the multidisciplinary field of nanotechnology, we relied on a database that indexed a total of 189,014 nanotechnology-related journal articles published in the two-year period of 2008-2009. This database of nanotechnology publications was built upon a set of bibliometric search terms that define the domain of nanotechnology-related publications.[54] Using this database, we identified a sample of 1,405 U.S.-affiliated authors of the most highly cited nanotechnology publications, each of whom was cited no fewer than thirty-nine times in the two-year period.

Data Collection

Data for the study were collected in two parts. First, a nationally representative survey of leading U.S. nano-scientists was collected by mail. The survey was fielded in four waves between June and September 2011, following Dillman, Smyth, and Christian's tailored design method.[55] A postcard announced the survey to nano-scientists and was followed by an initial mailing of the survey. Next, a postcard reminder was mailed to non-respondents three to four days after the initial mailing, followed by the second mailing of the survey after three to four weeks. The mail survey yielded 444 completed questionnaires, with a final response rate of 31.6%, following American Association for Public Opinion Research's method of response rate 3.[56] Such a response rate is not uncommon in the social sciences, particularly in elite or expert surveys.[57] We surveyed respondents about their perceived interactions with journalists and lay publics and the frequency with which they blogged about scientific research. The survey also focused on non-communication issues, such as respondents' perceptions about ethical, social, and policy implications of nanotechnology, which reduced the likelihood of a nonresponse bias.

In order to examine a link between scientists' public communication behaviors and indicators of scientific impact, we allowed respondents' *h*-indices to accumulate over a period of fifteen to eighteen months following our survey and thus collected the second part of our data in December 2012. We then gathered *h*-indices of all respondents from the Thomson Reuters Web of Science database and recorded cases in which their research was mentioned in tweets. Information from respondents' curricula vitae, obtained online from the institutions with which they were affiliated, was used to refine our *h*-index search. Our analysis focused only on scientists in tenure-track faculty positions, so scientists associated with private industry and in federal government positions (e.g., U.S. Department of Agriculture or U.S. Environmental Protection Agency) were excluded due to the lack of accessible curricula vitae. Our final sample was 241 U.S. nano-scientists.

Measures

Dependent variable. We used the *h*-index (M = 37.1, SD = 23.7) as a measure of a researcher's *scientific impact*.

Independent variables. Our questions about respondents' communication behaviors followed the measures of self-reported media use and face-to-face interactions used in previous communication research.[58] For the sake of simplicity, we use terms such as *public science communication* and *communication behaviors* in the remainder of this article to refer to self-reported communication activities. To obtain a measure of scientists' interactions with reporters, we asked respondents how often they spoke to reporters about their research findings, based on a 4-point scale (1 = *never*, 4 = *often*) (M = 2.6, SD = 0.9). *Interactions with other non-scientists* was measured by asking respondents how often they talked with non-scientists about their research findings, coded on the same scale (M = 3.1, SD = 0.7). *Science blogging* was gauged by asking respondents how frequently they wrote a blog about science, using the same 4-point scale (M = 1.3, SD = 0.6). We defined mentions on Twitter as tweets from any Twitter user that referenced the respondent's name and research with hyperlinks to detailed information. Due to the low number of tweets that mentioned respondents' research, we chose a dichotomous variable to indicate whether the participant's own research had been *mentioned on Twitter* (14.1% were mentioned on Twitter).

Control variables. We controlled for participants' *gender* (85.9% male), *scientific age* (the number of years since his or her first publication; M = 21.2, SD = 10.7), *tenure* (whether they were tenured faculty members; 73.8% tenured), and the *disciplinary field* in which they received their doctoral degree (33.1% chemistry, 17.6% engineering, 17.2% physics, 14.2% materials sciences, and 17.9% biology and other sciences) because of sensitivity of the h-index to each of these factors.[59] The disciplinary variables were entered in the regression model as a series of dummy variables, with biology and other sciences as the reference group.

Data Analysis

We tested our hypotheses and research questions using a hierarchical ordinary least squares (OLS) regression model. The variables were entered in blocks according to their assumed causal order. In the model, the blocks were ordered as follows:

1. Demographics and professional status (*gender, scientific age, tenure*)
2. Disciplinary field (chemistry, engineering, physics, materials sciences)
3. Public science communication (interactions with reporters, interactions with non-scientists, science blogging, mentioned on Twitter)
4. Two-way interactions

The final block included interaction terms that were created by multiplying standardized versions of the variables to minimize multicollinearity between the interaction terms and their components in the model.[60]

Table 1. Unique Variance Explained by Each Block in the OLS Regression Model Predicting *h*-Index (N = 241).

	R^2 (%)
Demographics and professional status	35.1***
Disciplinary field	0.8
Science communication	6.5***
Shared variance (%)	17.6***
Total variance (%)	60.0***

Note. OLS = ordinary least squares.
***$p \leq .001$.

Results

Overall, our model fit the data well, with variables included accounting for 60% of the variance in *h*-index. Most of the variance was accounted for by demographics and professional status (35.1%), while public science communication variables accounted for 6.5% of the variance in *h*-index (Table 1).

Scientific age ($\beta = .54$, $p \leq .001$) and tenure ($\beta = .14$, $p \leq .05$) were both positively related to scientific impact. Senior researchers, or those who had published their first paper earlier relative to others in the sample, had higher *h*-indices. Tenured scholars also had higher *h*-indices than those who were not tenured.

Our first research question (**RQ1**) was related to scientists' communication efforts through more traditional means, measured by their interactions with reporters. We found a positive relationship between interactions with reporters and *h*-indices ($\beta = .22$, $p \leq .001$), implying that scholars who had more interactions with reporters had greater scientific impact than those who had fewer interactions with reporters. Neither interactions with other non-scientists nor science blogging was significantly related to *h*-indices (Table 2). Thus, **H1** and **H2** were not supported.

As hypothesized in **H3**, scientists whose research was mentioned on Twitter had significantly higher *h*-indices ($\beta = .13$, $p \leq .01$) than their peers whose research was not mentioned on Twitter (Table 2). In response to our second research question (**RQ2**) on the moderating effects of different forms of public communication on the *h*-index, we found two significant interactions (Table 2). The interactive effect between scientists' interactions with reporters and being mentioned on Twitter was positive ($\beta = .14$, $p \leq .05$). Interactions with reporters had a significantly higher impact on the *h*-index for those scientists who were also mentioned on Twitter than for those who were not (Figure 1). Being mentioned on Twitter also further amplified the effect of interactions with other non-scientists on the *h*-index ($\beta = .11$, $p \leq .05$). In other words, the *h*-indices of scientists who interacted with other non-scientists were higher if they were also mentioned on Twitter, compared with scholars who were not (Figure 2).

Table 2. OLS Regression Model Predicting *h*-Index (*N* = 241).

	Zero-order	β
Block 1: Demographics and professional status		
Gender (female = 1)	−.08	.02
Scientific age	.70***	.54***
Tenure (tenured = 1)	.54***	.14*
Incremental R^2 (%)		*51.2****
Block 2: Disciplinary field		
Chemistry	.04	−.02
Engineering	−.13	−.10
Physics	.04	−.05
Material Science	−.06	−.07
Incremental R^2 (%)		*0.2*
Block 3: Science communication		
Interactions with reporters	.34***	.22***
Interactions with other non-scientists	.18**	.02
Science blogging	−.03	−.06
Mentioned on Twitter (mentioned = 1)	.23***	.13**
Incremental R^2 (%)		*6.5****
Block 4: Two-way interactions		
Interactions with reporters × Interactions with non-scientists	—	.08
Interactions with reporters × Science blogging	—	.01
Interactions with reporters × Mentioned on Twitter	—	.14**
Interactions with non-scientists × Science blogging	—	.03
Interactions with non-scientists × Mentioned on Twitter	—	.11*
Science blogging × Mentioned on Twitter	—	.04
Total R^2 (%)		*60.0****

Note. Cell entries are final standardized regression coefficients for blocks 1, 2, and 3 and before-entry standardized regression coefficients for block 4. OLS = ordinary least squares.
*$p \leq .05$. **$p \leq .01$. ***$p \leq .001$.

Discussion

In this study, we surveyed the most highly cited U.S. nano-scientists and explored the effects of scientists' public communication behaviors via traditional and new media on their scientific impact as measured by the *h*-index. The current study provides the first comprehensive empirical evidence that outreach activities, such as interactions with reporters and being mentioned on Twitter, can assist a scientist's career by promoting his or her scientific impact. More importantly, online buzz (e.g., being mentioned on

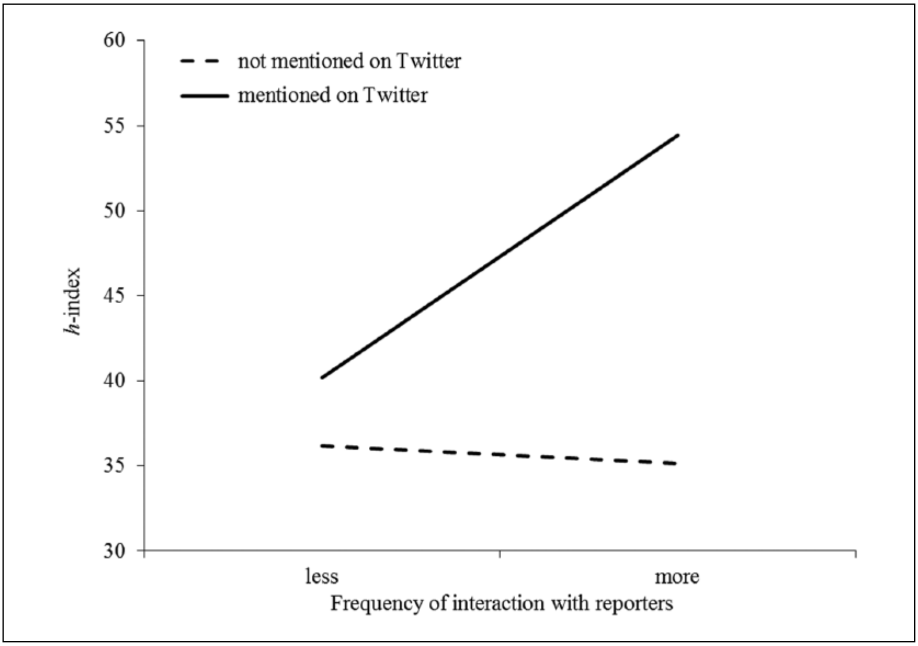

Figure 1. Interactive effect between frequency of interaction with reporters and being mentioned on Twitter on *h*-index.
Note. Scale on *Y*-axis only is partially displayed.

Twitter) further amplifies the impact of communicating science through traditional outlets on the scholar's scientific impact. Neither science blogging nor interacting with non-scientists had any significant effect on scientific impact, which could be explained by the inherent complexity of each of the two forms of activities. The readership of science blogs may vary greatly from one post to another, and similarly, "interaction with non-scientists" can be wide-ranging (such as talking to family members and collaborating with industry professionals). If this is indeed the case, these two forms of communication activities are not consistently related to scientists' academic impact.

Before elaborating on the implications of our findings, it is important to discuss several limitations of the current work. First, the *h*-index is not a perfect indicator of scientific impact and should be interpreted with caution. In general, the recognized problems with the *h*-index include its potential to hamper the measured impact of scientists who have published a small number of papers and its bias across disciplines that have different inherent citation patterns.[61] Our sample design (specifically focusing only on the most highly cited authors) and controls in the regression model (e.g., scientific age and disciplines) was constructed to minimize such biases. Despite the potential limitations, the *h*-index is able to give relatively reliable information about the scientific impact of a given researcher, and is recognized as an improvement in

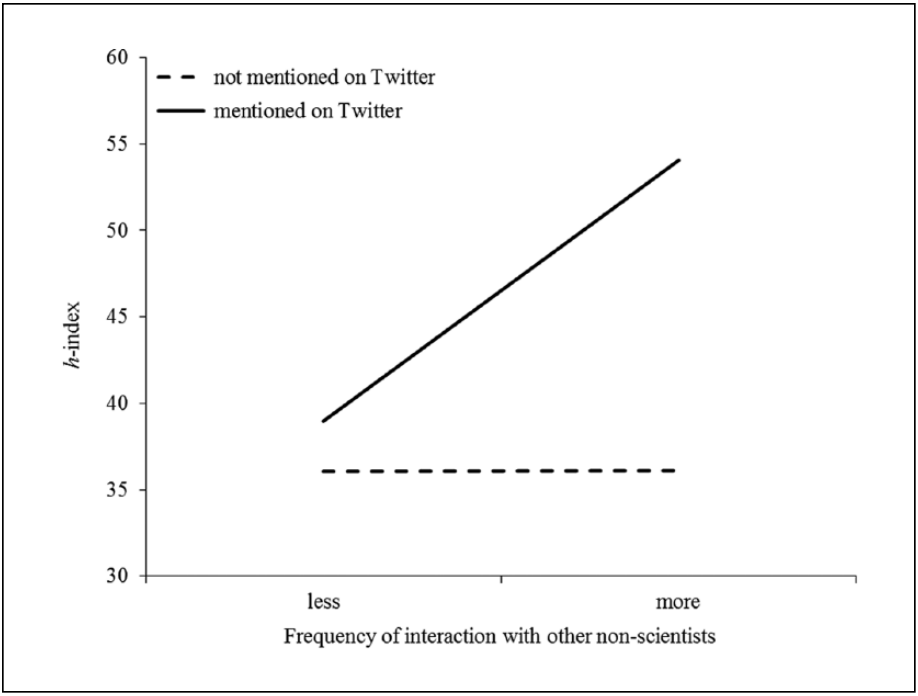

Figure 2. Interactive effect between frequency of interaction with other non-scientists and being mentioned on Twitter on *h*-index.
Note. Scale on *Y*-axis only is partially displayed.

comparison with many other available indices of scientific impact, such as total citation count, citations per paper, and total paper count.[62] As noted previously, the *h*-index has a linear and positive relationship with a scholar's scientific age.[63] The significant relationship we found between the *h*-index and scientific age demonstrates the construct validity of the *h*-index measure used in our study.

A second concern is related to our relatively small sample size and the generalizability of our findings. The present sample design includes only university-based scientists, which does not allow us to compare subgroups of scientists based on their affiliations with industry or other non-academic institutions. Despite the relatively small sample size, our sample and data are unique and valuable in that we were successful in collecting data from hard-to-reach experts. To our knowledge, there are no previous studies that evaluate the effect of communication efforts on scientific impact that match our research design. More importantly, our sample design is also a strength because it attenuates potential concerns about endogeneity by limiting our analyses to a group of already highly visible scientists. The issue of endogeneity, if not addressed appropriately, could confound our evaluation of the effects of various communication behaviors on one's scientific impact. Some confounding factors, such as scientists' educational institutions, professional status, and *h*-indices scientists have accumulated in previous years, could be highly correlated with one's communication behaviors and *h*-indices in the following years. In other words, these scientists were likely to come from elite educational institutions, have published a number of highly impactful papers, and were therefore covered more frequently in the media.

In this study, the issue of endogeneity is minimized in three ways. First, as presented above, we focused on a heterogeneous sample of the most highly cited scientists. Second, we collected scientists' *h*-indices about one-and-a-half years after surveying their communication behaviors. Third, we controlled for the factors that might be correlated with both scientists' communication behaviors and their scientific impact, for example, gender and professional status (scientific age, whether the respondent was tenured, and disciplinary field). As a result, we observed a significant and positive association between active communication behaviors and the *h*-index after their communication behaviors. It is reasonable to assume that the strength of the observed associations would increase if we adopted a longer time period to allow *h*-indices to accumulate following various communication behaviors.

Furthermore, it is important to take into account the nature of our operationalization of activities on Twitter. Ideally, we would like to have included continuous measures of both active and passive Twitter activities, that is, scientists' tweeting research updates to their followers, as well as being mentioned in others' tweets. However, too few scientists were active Twitter users to include either active Twitter use or a continuous measure (as opposed to our dichotomous indicator) of Twitter mentions in our study. The limited number of respondents using Twitter was unsurprising, given that tweeting about scientific research is a relatively recent phenomenon within academia, and currently 16% of the general population are on Twitter.[64] Nonetheless, Twitter should still be viewed as a critical platform for science information exchange and public science communication, due in part to the sheer volume of science-related posts on Twitter; for example, there were over 495,000 nanotechnology-related opinions shared on Twitter over just one year between September 1, 2010, and August 31, 2011.[65] More importantly, the number of Twitter users has grown at an enormous rate, with the proportion of Internet users who are on Twitter doubling since the end of 2010.[66] On these bases, the influence of tweeted nano-related information can be important. As noted above, we did not focus on how each single tweet affects the impact of single news stories in traditional media or how the salience of scientific issues transfers from one medium to another. Instead, we aimed to answer a more important question: the overall effect of Twitter activities on the link between traditional communication efforts and scientific impact.

Mindful of the limitations of the current study, the primary finding that the professional status of nano-scientists may benefit from mass media interactions contrasts with the conclusions made within prior science communication literature.[67] This is particularly important when mass communication is undergoing significant transformation and science is expanding its role in society. Nowadays, collaborations between journalists and scientists are increasingly frequent,[68] despite the shrinking science-related news hole in the mass media. Almost all the two thousand members of the

National Association of Science Writers are freelancers who depend on working relationships with individual scientists as information sources.[69] The positive link between scientist–journalist interactions and scientific impact may, therefore, encourage scientists' engagement with science communication through legacy media, which will ultimately serve lay audiences as well.

Another significant finding of this study indicates that increasing use of online media compared with legacy media may be impacting contemporary science communication. In Web 2.0, the boundaries that separated scientists, journalists, and the public may be blurring. Our findings suggest there is value in "building buzz" by utilizing social media as well as legacy mass communication channels to enrich information exchanges between the scientific community and public audiences. Many scholars have suggested that social media are supplementing rather than supplanting conventional channels, such as newspapers and television, for scientific information.[70] For the moment, this may be true. In particular, social media can augment the impact of more conventional forms of public communication as demonstrated in this study.

Yet social media may also present the scholarly community with new challenges related to traditional metrics of success. In academic circles, book blurbs from well-known scholars or book reviews by prestigious media outlets are generally considered more impactful than those from less well-known entities. A similar logic applies to social media. If a scientist's work is tweeted by prominent science reporters (such as Andrew Revkin, who has more than 50,000 followers on Twitter), scientists (such as Neil deGrasse Tyson with more than 1.5 million followers on Twitter), or science media outlets (such as *Science Friday* with over 446,000 followers on Twitter), it is likely to attract more attention and have a larger impact even within academic circles, than a study that was only published in a peer-reviewed academic outlet (even for elite outlets, such as *Nature* and *Science* with impact factors of 36.28 and 31.2, respectively). The rewards for public communication efforts on social media may eventually force academics to think more carefully about mapping academic impact in a world of sites, such as Google Scholar and ResearchGate.com, which combine social media metrics with indicators of scholarly productivity to measure the broader impact of academic work. Indeed, some scholars have recently called for social media to be used to supplement traditional approaches to measuring academic impact.[71]

Nonetheless, it is noteworthy that current online social media environments may have potential pitfalls for science communicators, and mass communication at large. Open and interactive dialogues inherent to Web 2.0 tools like Twitter and Facebook enable audiences to repurpose and translate scientists' research findings using their own interpretations and debate them on social media.[72] Thus, social networks can also help spread potential misinterpretations of scientific findings quickly among large audiences. For example, some scholars have raised concerns that readers' uncivil online comments following scientific information on social media can polarize perceptions of risks associated with a technology[73] and even bias perceptions of source and message credibility.[74]

Future research could conduct a more fine-grained exploration of scientists' public outreach efforts with sophisticated data collection. For example, a study can include more time points to collect data of different patterns of communication behaviors associated with both traditional media and new media to explore how each behavior sequentially affects scholars' scientific impact. The variation in institutional and disciplinary culture should also be given consideration. A larger sample size would allow for more careful examination of the specific attributes of scientists across disciplines and affiliations. Comparing the impacts of outreach activities for scientists with different affiliations (such as an industry-based, government-based, versus university-based comparison) and from other research disciplines could yield distinct findings. In addition, future scholarship should use precise measurements of scientists' communication behaviors. In particular, measures with a reference point and actual frequencies (e.g., times per month) would capture actual public communication behaviors by scientists. Finally, we encourage attempts to obtain continuous variables of both active and passive activities on social media, such as frequencies of reposting one's own research, posting comments on others' research, and mentions of one's research. These approaches could yield valuable results about the impact of various increasingly popular social media (such as Facebook, Twitter, and Google Plus) on scientists' careers.

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