On the quest for currencies of science: field "exchange rates" for citations and Mendeley readership

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ABSTRACT

Purpose
The introduction of "altmetrics" as new tools to analyze scientific impact within the reward system of science has challenged the hegemony of citations as the predominant source for measuring scientific impact. Mendeley readership has been identified as one of the most important altmetric sources, with several features that are similar to citations. In this paper we perform an in-depth analysis of the differences and similarities between the distributions of Mendeley readership and citations across fields.

Method
We analyze two issues, using in each case a common analytical framework for both metrics: (i) the shape of the distributions of readership and citations, and (ii) the field-normalization problem generated by differences in citation and readership practices across fields. In the first issue we use the Characteristic Scores and Scales method, and in the second the measurement framework introduced in Crespo et al. (2013).

Findings
There are three main results. Firstly, the citations and Mendeley readership distributions exhibit a strikingly similar degree of skewness in all fields. Secondly, the results on "exchange rates" for Mendeley readership empirically supports the possibility of comparing readership counts across fields, as well as the field normalization of readership distributions using exchange rates as normalization factors. Thirdly, field normalization using field mean readerships as normalization factors leads to comparably good results.

Originality
These findings open up challenging new questions, particularly regarding the possibility of obtaining conflicting results from field-normalized citation and Mendeley readership indicators; this suggests the need for better determining the role of the two metrics in capturing scientific recognition.

INTRODUCTION

In 1998 Garfield stated that "*[t]he Mertonian description of normal science describes citations as the currency of science. Scientists make payments, in the form of citations, to their preceptors*". The idea of citations as the *currency of science* was also discussed one year later by Wouters (1999), according to whom "*the role of the citation might also be compared with that of money, especially if the evaluative use of scientometrics is taken into account. Whenever the value of an article is expressed in its citation frequency, the citation is probably the most important unit of a 'currency of science'*". Thus, citations are often seen as a means for rewarding scientists for their work and scientific merit, so that, together with authorship and acknowledgements, they have become an integral part of the so-called "reward triangle" (Cronin & Weaver, 1995).

This role of citations as the main currency in evaluative scientometrics has gone unchallenged for many years. The recent emergence of new ways of measuring the reception of scientific publications by different audiences in the form of the so-called "altmetrics" (Haustein *et al.*, 2015; Priem *et al.*, 2010) probably represents the most important attempt at expanding the system of scientific currencies. This development of new indicators, aimed at capturing broader perspectives of the symbolic capital of scientists' outputs, may cause a change in the "rules" and "norms" of a more multifaceted reward system of science, where different forms of symbolic capital might interplay in the representation of the esteem and recognition of scientific agents (Desrochers *et al.*, 2015).

However, in spite of the initial expectations regarding altmetrics as potential alternatives to citations (Priem *et al.*, 2010), recent research on the most important social media metrics (e.g. Twitter, Facebook, blogs, etc.) suggests that there are fundamental differences with citations: in coverage (Thelwall *et al.*, 2013), main characteristics (Haustein *et al.*, 2015), correlations (Costas *et al.*, 2015b; Haustein *et al.*, 2014), and interpretation within the scientific reward system (Haustein *et al.* 2016). These results essentially highlight the limited potential of most of these metrics as realistic alternatives to citations. Consequently, their role has been relegated to complementary metrics capturing aspects that are not covered by citations (Cronin, 2013; Torres-Salinas *et al.*, 2013; Costas *et al.*, 2015; Haustein *et al.*, 2014).

There is however an altmetric source that has been highlighted as an exception to this pattern: *Mendeley readership*. The Mendeley database, identified as one the most important sources of alternative metrics (Wouters & Costas, 2012; Torres-Salinas *et al.*, 2013), has been found to have a high coverage of scientific publications (i.e. a large share of publications have some readership in Mendeley, cf. Zahedi *et al.*, 2014), there are moderate correlations between readership and citations (Zahedi *et al.*, 2014; Li *et al.*, 2012), and readership scores have also a good filtering ability of highly cited publications (Zahedi *et al.*, 2015). Field differences in the presence of Mendeley readership (Costas *et al.*, 2015a), and the technical possibilities of calculating field-normalized Mendeley readership indicators (Fairclough & Thelwall, 2016; Bornmann & Haunschild, 2016; Haunschild & Bornmann, 2016) have also been discussed in the literature. Consequently, it becomes highly relevant to study the characteristics of field readership distributions and to test the feasibility of alternative field normalization strategies with the same techniques used for studying and normalizing field citation distributions.

OBJECTIVES

This paper has three objectives. Firstly, to study whether field Mendeley readership distributions for a large set of Web of Science (WoS) publications are as highly skewed and as similar across fields as is found for field citation distributions. Secondly, to explore the possibility of overcoming the field dependence of Mendeley readership practices by estimating "exchange rates" for comparing Mendeley readership counts across fields as has been done for comparing citation counts. Thirdly, to compare the consequences for field normalization of using Mendeley exchange rates and mean readership as normalization factors.

METHODOLOGY

Data and analytical approach

We consider a total of 1,125,811 distinct publications labeled as 'articles' in the WoS from year 2012, with a DOI and belonging to any of the 30 broad fields used by Ruiz-Castillo & Costas (2014)[1]. The problem of the assignment of publications to more than one field category is solved following a multiplicative approach (cf. Herranz & Ruiz-Castillo, 2012). The corresponding extended count in the final dataset consists of 1,634,932 records, whose distribution by field is presented in columns 1 and 2 in Table 1. Citation scores and Mendeley[2] readership scores have been computed considering variables windows for both metrics (up to July 2015 for readership and August/September 2015 for citations).

Table 1. The distribution of the total number of articles by field, and mean citation and readership values for all fields and the overall population of publications

Field	N	%N	μ_1 Citations	μ_2 Citations	μ_1 Mendeley	μ_2 Mendeley
	(1)	(2)	(3)	(4)	(5)	(6)
AGRICULTURE AND FOOD SCIENCE	44,998	2.8%	7.3	16.2	11.6	26.2
ASTRONOMY AND ASTROPHYSICS	18,646	1.1%	12.7	29.7	6.4	14.9
BASIC LIFE SCIENCES	148,768	9.1%	11.4	27.7	17.9	47.1
BASIC MEDICAL SCIENCES	29,570	1.8%	8.6	19.0	12.4	28.6
BIOLOGICAL SCIENCES	78,224	4.8%	9.0	23.0	20.2	51.3
BIOMEDICAL SCIENCES	144,606	8.8%	9.7	22.0	13.9	34.1
CHEMISTRY AND CHEMICAL ENGINEERING	180,603	11.0%	10.5	25.6	9.6	24.1
CIVIL ENGINEERING AND CONSTRUCTION	13,223	0.8%	5.4	12.5	9.8	22.4
CLINICAL MEDICINE	269,121	16.5%	8.8	21.4	10.3	24.1
COMPUTER SCIENCES	39,050	2.4%	5.1	14.3	12.7	32.8
EARTH SCIENCES AND TECHNOLOGY	49,992	3.1%	8.0	17.6	14.1	34.0
ECONOMICS AND BUSINESS	21,881	1.3%	4.7	11.8	19.0	48.1

[1] This classification is based on the partition of the original WoS journal subject categories into broad fields as in Tijssen *et al*. (2010).
[2] As in Zahedi & van Eck (2014), we use Mendeley REST API based on the matching of the DOIs of publications. Publications with no matching in Mendeley are considered to have zero readership.

Field	N	%N	μ_1 Citations	μ_2 Citations	μ_1 Mendeley	μ_2 Mendeley
	(1)	(2)	(3)	(4)	(5)	(6)
EDUCATIONAL SCIENCES	12,263	0.8%	4.1	10.6	17.1	36.9
ELECTRICAL ENGINEERING AND TELECOMMUNICATION	55,140	3.4%	4.8	11.8	7.4	20.3
ENERGY SCIENCE AND TECHNOLOGY	26,092	1.6%	8.9	21.3	12.1	29.3
ENVIRONMENTAL SCIENCES AND TECHNOLOGY	68,920	4.2%	8.8	20.2	20.2	49.6
GENERAL AND INDUSTRIAL ENGINEERING	15,310	0.9%	4.7	10.7	9.1	23.4
HEALTH SCIENCES	38,109	2.3%	6.3	14.7	13.7	27.6
INFORMATION AND COMMUNICATION SCIENCES	5,088	0.3%	4.3	11.2	20.6	45.2
INSTRUMENTS AND INSTRUMENTATION	14,246	0.9%	6.3	16.4	8.2	22.5
LAW AND CRIMINOLOGY	5,398	0.3%	3.8	8.5	9.7	19.6
MANAGEMENT AND PLANNING	10,943	0.7%	4.8	11.4	24.2	56.2
MATHEMATICS	42,060	2.6%	3.3	9.3	3.3	12.3
MECHANICAL ENGINEERING AND AEROSPACE	32,689	2.0%	5.1	12.5	6.7	16.2
PHYSICS AND MATERIALS SCIENCE	197,288	12.1%	8.5	22.3	8.6	23.1
PSYCHOLOGY	32,068	2.0%	7.1	16.7	22.0	47.9
SOCIAL AND BEHAVIORAL SCIENCES, INTERDISCIPLINARY	8,143	0.5%	5.1	12.1	15.6	31.7
SOCIOLOGY AND ANTHROPOLOGY	13,107	0.8%	4.6	11.5	16.1	36.7
STATISTICAL SCIENCES	19,386	1.2%	5.6	15.2	12.4	35.6
Total	1,634,932	100.0%	8.4	21.0	12.5	32.0

We use the following two analytical approaches.

1) *Characteristic Scores and Scales analysis*

The Characteristic Scores and Scales technique (CSS hereafter) is used (Glänzel & Schubert, 1988) to analyze the shape of field citation/readership distributions abstracting from size and scale differences. We partition each citation/readership distribution into three broad categories: (C1) publications with low citations/readership smaller than or equal to μ_1 (mean of the metric for the entire distribution); (C2) fairly cited/read publications, with citations/readership greater than μ_1 and smaller than or equal to μ_2 (mean of the metric with scores above μ_1); and (C3) publications with remarkable scores greater than μ_2.

Citation/readership distributions are described by means of two sets of statistics: the percentage of publications in each of the three categories, and the percentage of the total number of citations/readership attributed to the publications in each category. We assess the between-field similarity using the coefficient of variation (CV hereafter) of the six statistics over the 30 fields.

2) *'Exchange rate' estimation and field normalization of raw citation and readership counts*

Crespo *et al.* (2013) introduce a measuring framework for estimating the effect on overall citation inequality of differences in citation practices across scientific fields. The striking similarity between field citation distributions documented at different aggregation levels (Glänzel, 2007, Albarrán & Ruiz-Castillo, 2011, Albarrán *et al.*, 2011, Radicchi & Castellano, 2012, Li *et al.*, 2013, and Ruiz-Castillo & Waltman, 2015), causes the effect on citation inequality of differences in citation practices to be approximately constant over a wide interval of intermediate quantiles in the support of citation distributions. This allows such an effect to be quite well estimated over that interval by means of a set of *citation exchange rates*. In the metaphor according to which a field's citation distribution is like an income distribution in a certain currency, such exchange rates permit all citations to be expressed in the same reference currency.

This paper shows that this framework is equally useful for quantifying the effect on overall readership inequality of differences in Mendeley readership practices across fields. Moreover, the similarity between field readership distributions allows estimation of a set of *readership* or *Mendeley exchange rates* over a relevant interval that serve to answer the following two questions. Firstly, how many readership counts in a given field are equivalent to, say, one readership count in the all-fields case (i.e. all articles as a whole)? Secondly, how much can we reduce the effect on overall readership inequality of differences in readership practices by normalizing the raw readership data with the Mendeley exchange rates?

In our final contribution, we analyze the field-normalization procedure in which average readership counts are used as normalization factors.

RESULTS

Distribution of citations and readerships across fields – CSS analysis

The means μ_1 and μ_2 for each field and the all-fields distribution for both metrics are presented in columns 3 to 6 in Table 1. An important first observation is that for most fields the mean readership is higher than the mean citation scores, corroborating previous results on the higher density of Mendeley readership over citations (Costas *et al.*, 2015a; Mohammadi & Thelwall, 2014; Zahedi *et al.*, 2015). In line with previous research (Costas *et al.*, 2015a; Thelwall & Sud, 2015; Haustein & Larivière, 2014), our results confirm that there are substantial disciplinary differences in the values and density of citations and Mendeley readerships across fields.

The large differences in field size and field means observed in Table 1 justify the use of size- and scale-independent techniques –such as CSS– for analyzing citation and readership distributions. CSS results for field citation and readership distributions are available in Tables A and B in the Appendix, while average results and the corresponding CVs over the 30 fields for both metrics are presented in Table 2.

Table 2. The skewness of citation and readership distributions according to the CSS approach. Percentages of articles and citations/readerships by category. Average and CV over the 30 fields.

CITATION DISTRIBUTIONS	Percentage of articles in:	Percentage of total citations in:

	C1	C2	C3	C1	C2	C3
Average	69.2%	21.9%	8.8%	25.4%	33.7%	40.8%
CV	0.03	0.06	0.13	0.10	0.03	0.06
MENDELEY READERSHIP DISTRIBUTIONS	**Percentage of articles in:**			**Percentage of total readership in:**		
	C1	**C2**	**C3**	**C1**	**C2**	**C3**
Average	69.7%	21.7%	8.7%	26.6%	33.1%	40.4%
CV	0.04	0.08	0.10	0.10	0.03	0.07

As illustrated in Figures 1 (citations) and 2 (readership), all field distributions are highly skewed and their shapes are remarkably similar for both metrics. Specifically, for citations we find that, on average, 69% of all publications belong to C1 and account for approximately 25% of all citations, while 9% of the publications are in C3 concentrating 41% of all citations. Interestingly enough, virtually the same values are found for readership. The fairly small CVs speak eloquently about the similarity across fields of the distributions of both metrics. This remarkable between-field similarity paves the way for the meaningful comparisons of each metric between the 30 scientific fields explored in the next section.

Figure 1. Partition of citation distributions into three categories

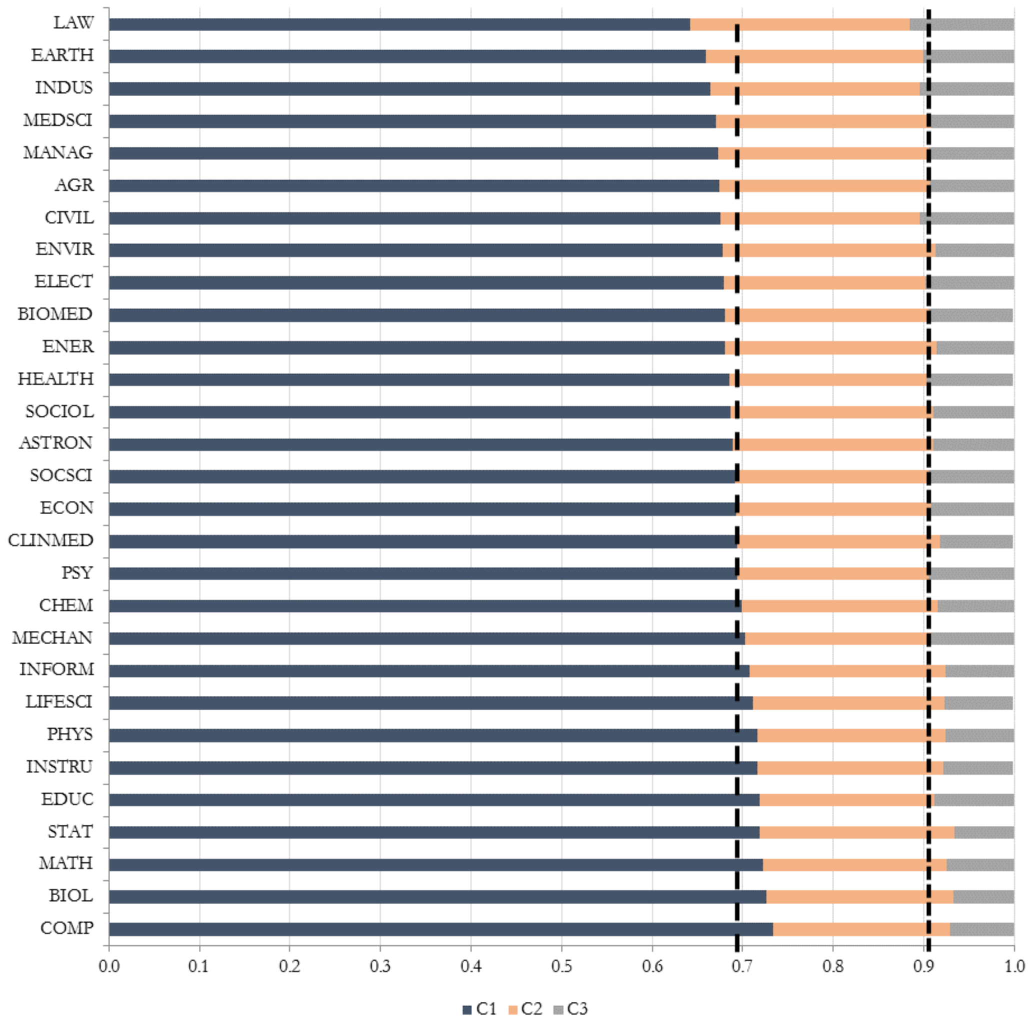
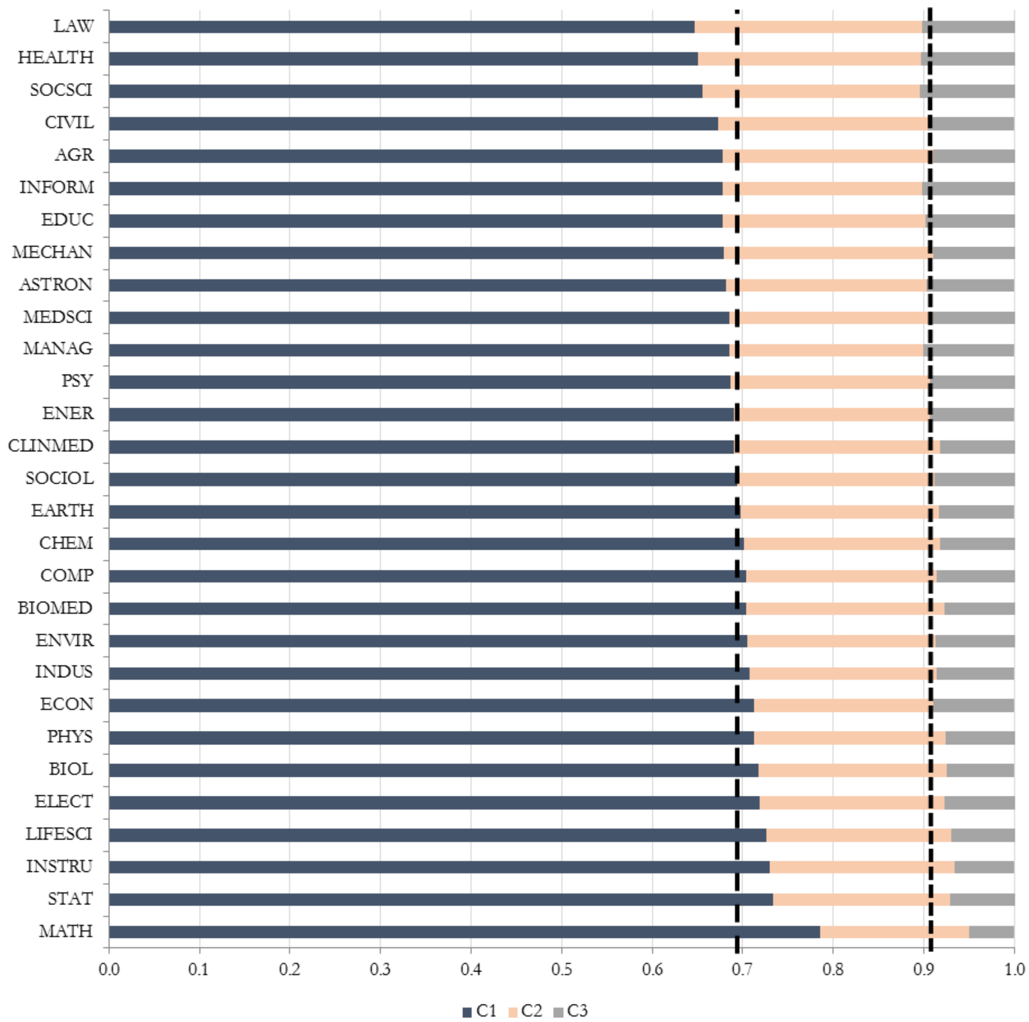

LAW
EARTH
INDUS
MEDSCI
MANAG
AGR
CIVIL
ENVIR
ELECT
BIOMED
ENER
HEALTH
SOCIOL
ASTRON
SOCSCI
ECON
CLINMED
PSY
CHEM
MECHAN
INFORM
LIFESCI
PHYS
INSTRU
EDUC
STAT
MATH
BIOL
COMP
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
C1 C2 C3

Figure 2. Partition of Mendeley readership distributions into three categories



It should be noted that these results are comparable with those obtained in previous research concerning field citation distributions at different aggregation levels, research institutions and countries (Glänzel *et al.*, 2014, Perianes-Rodriguez & Ruiz-Castillo, 2015, and Albarrán *et al.*, 2015), and the productivity of authors (Ruiz-Castillo & Costas, 2014). That Mendeley readership is skewed to citations is also supported by Thelwall & Wilson (2015) for Medical articles.

Comparison of citation and readership counts across fields – “Exchange rates” analysis

This section consist of two parts, where we discuss (i) the measurement framework of the effect on overall citation/readership inequality of differences in citation/readership practices across fields, and (ii) the estimation of two sets of citation/readership exchange rates.

The measurement framework

Let fields be indexed by f = 1,…, 30, and let c_f and r_f be the ordered citation and readership distributions of field f, so that $C = \{c_f, f = 1,\dots, 30\}$ and $R = \{r_f, f = 1,\dots, 30\}$ are the overall citation and readership distributions in the all-fields case. The Crespo *et al.* (2013) framework is equally valid for the measurement of the effect on the overall citation inequality of distribution C of differences in citation practices, or the measurement on the overall readership inequality of distribution R of the effect of differences in readership practices. However, in what follows we summarize the framework in a novel case for readership distributions.

Let us partition each readership distribution r_f into Π quantiles of equal size, $r^{\pi}{}_f$, indexed by π = 1,…, Π. In practice, we take the percentiles, so that $\Pi = 100$. As we will see below in the numerical part, the method applies the additive decomposability property of a certain member of the Generalized Entropy family of citation inequality indices –denoted by I– to the double partition of distribution R into fields and quantiles.

Assume for a moment that, in any field f we disregard the readership inequality within every percentile π by assigning to every article in that percentile the mean citation of the percentile itself, μ_f^{π}. For any π, all quantities μ_f^{π}, f = 1,…, 30 are comparable because they represent the mean readership of publications belonging to the same percentile π in the corresponding readership distribution r_f. Thus, the interpretation of the fact that, for example, $\mu_j^{\pi} = 2\,\mu_l^{\pi}$ is that, on average, the readership impact of field j is twice as large as the readership impact of field l in spite of the fact that both quantities represent a common underlying phenomenon, namely, the same *degree* π *of* readership *impact or* (*readership*) *excellence* in both fields. In other words, for any π, the difference between μ_j^{π} and μ_l^{π} is entirely attributable to the differences in the idiosyncratic readership practices that prevail in the two fields for publications having the same degree of excellence. Thus, the readership inequality between fields at each percentile

$$I(\pi) = I(\mu_1^{\pi},\dots, \mu_f^{\pi},\dots, \mu_{30}^{\pi})$$

is entirely attributable to the differences in readership practices between the 30 fields, holding constant the degree of excellence in all fields at percentile π. Hence, the graphical representation of the term $I(\pi)$ as a function of π allows us to assess the impact on readership inequality of differences in readership practices at all percentiles π = 1,…, 100.

In our case, expressions $I(\pi)$ for both metrics are represented by the blue lines in Figure 3 (citations) and Figure 4 (readership). Since these expressions reach very high values at the lower tail of citation distributions, for clarity both Figures start at the 30^{th} percentile.

Figure 3. Citation inequality due to differences in citation practices across fields, $I(\pi)$, as a function of π. Raw and field-normalized data for Web of Science citations

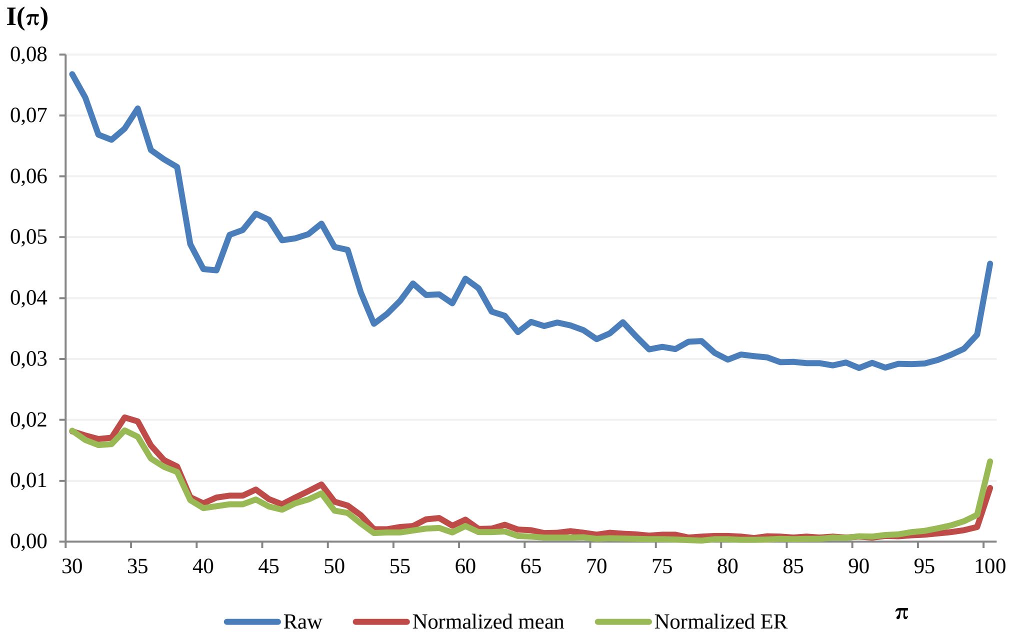
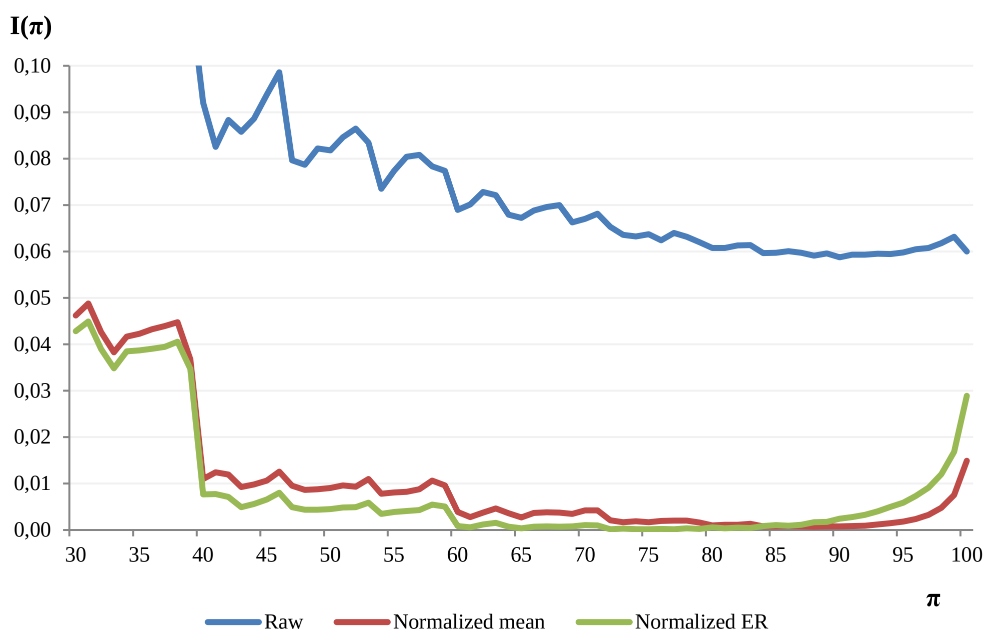


Figure 4. Readership inequality due to differences in readership practices across fields, $I(\pi)$, as a function of π. Raw and field-normalized data for Mendeley readership



The above graphical procedure has the advantage that no value judgment is used to weight differences between two expressions $I(\pi)$ and $I(\pi')$ at different percentiles, say π and π'. However, the comparison of entire lines is somewhat cumbersome. Thus, Crespo *et al.* (2013) propose a numerical estimate of the effect on overall readership inequality, $I(R)$, which can be attributed to differences in readership practices through a term denoted *IDRP* (*I*nequality due to *D*ifferences in *R*eadership *P*ractices). It can be shown that $I(R)$ can be expressed as the sum of three terms, one of which is the *IDRP* term defined as follows:

$$IDRP = \Sigma_{\pi} v^{\pi} I(\pi)$$

where, for each π, v^{π} is the share of total readership counts received by articles in quantiles r^{π}_{f} for all f, so that $\Sigma_{\pi} v^{\pi} = 1$. Therefore, the term *IDRP* is a weighted average of the quantities $I(\pi)$, with weights v^{π} that add up to one. It should be noted that, due to the skewness of readership distributions analyzed in the previous section, in practical applications the weights v^{π} tend to increase dramatically with π.

In any case, for assessing the relative effect on the overall readership inequality $I(R)$ attributed to the differences in readership practices across fields we use the ratio

$$IDRP/I(R).$$

In the citations case, the corresponding quantities are denoted *IDCP* (*I*nequality due to *D*ifferences in *C*itations *P*ractices) and $I(C)$. Table 3 contains the numerical results for both metrics.

Table 3. Overall citation/readership inequality decomposition

	IDCP, IDRP	**$I(C)$, $I(R)$**	**100*[(1)/(2)]**
	(1)	**(2)**	**(3)**
CITATIONS	0.04	0.75	5.3
MENDELEY READERS	0.07	0.77	9.1

Relative to overall citation/readership inequality, the importance of the effect of differences in citation/readership practices ranges from 5.3% in WoS citations, to 9.1% in Mendeley readership. It should be noted that, relative to overall citation inequality, the order of magnitude of the *IDCP* term is smaller than in Crespo *et al.* (2013) for a similar number of broad scientific disciplines. However, the latter uses a much larger dataset of 4.4 million articles (without the DOI restriction) published in 1998–2003 with a five-year citation window. Naturally, the order of magnitude of the *IDCP* term increases with the size of the classification system (Li *et al.*, 2013; Crespo *et al.*, 2014; Perianes-Rodriguez & Ruiz-Castillo, 2016a, 2017).

The comparison of citation and readership counts across fields. Definition and estimation of the exchange rates for both metrics

The key idea in Crespo *et al.* (2013) is that mean readership of comparable articles belonging to the same quantile can be used to express the readership in any field in terms of the readership in a reference situation. For example, if we let μ^{π} be the mean readership of all articles in quantile π, then the *exchange rates at quantile* π, $e_f(\pi)$, defined by

$$e_f(\pi) = \mu_f^{\pi} / \mu^{\pi},$$

can be seen to answer the following question: how many readership counts for an article at the degree π of readership impact in field *f* are equivalent on average to one readership count in the all-fields case?

Naturally, if for many fields $e_f(\pi)$ were to drastically vary with π, then we might not be able to claim that differences in citation practices have a common element that can be precisely estimated. However, we next establish that exchange rates are sufficiently constant over some interval $[\pi_m, \pi^M]$. In this situation, it is reasonable to define an average-based *exchange rate* (*ER* hereafter) over that range as

$$e_f = [1/(\pi^M - \pi_m)]\ [\Sigma_{\pi}\, e_f(\pi)]. \qquad (1)$$

An advantage of this definition is that we can easily compute the associated standard deviation denoted by σ_f. The fact that, for each *f*, the $e_f(\pi)$ defined in (1) are very similar for all π in the interval $[\pi_m, \pi^M]$ would manifest itself in a small σ_f, and hence in a small coefficient of variation $CV_f = \sigma_f / e_f$.

Similar to previous studies (Crespo *et al.*, 2013, 2014; Albarrán *et al.*, 2015; Perianes-Rodriguez & Ruiz-Castillo, 2016a, 2016b, 2017), in Figures 3 and 4 it is observed that $I(\pi)$ is particularly high until $\pi \approx 60$, as well as for a few quantiles at the very upper tail of citation distributions. However, $I(\pi)$ is relatively similar for a wide range of intermediate values[3]. In our case, we find that the choice of a common interval $[\pi_m, \pi^M]$ = [50, 97] for both metrics is a good one. The ERs and the CVs for citations (ERc) and Mendeley readership (ERm) in that interval are presented in Table 4[4]. We find it useful to divide fields into three groups: Group I (in green in Table 4), has a *CV* smaller than or equal to 0.05. This means that the standard deviation of the ER is less than or equal to five percent of the ER itself. Hence, we consider ERs in this group as highly reliable. Group II (yellow), has a CV between 0.05 and 0.10. We consider ERs in this group as fairly reliable. Group III (red), with a CV greater than 0.10, must be considered as somewhat unreliable.

[3] It is important to emphasize that this is consistent with the stylized facts characterizing citation distributions discussed in the CSS analysis: although the percentages of articles belonging to three broad classes are very similar across fields, citation and Mendeley readership distributions are rather different in a long lower tail and at the very top of the upper tail.

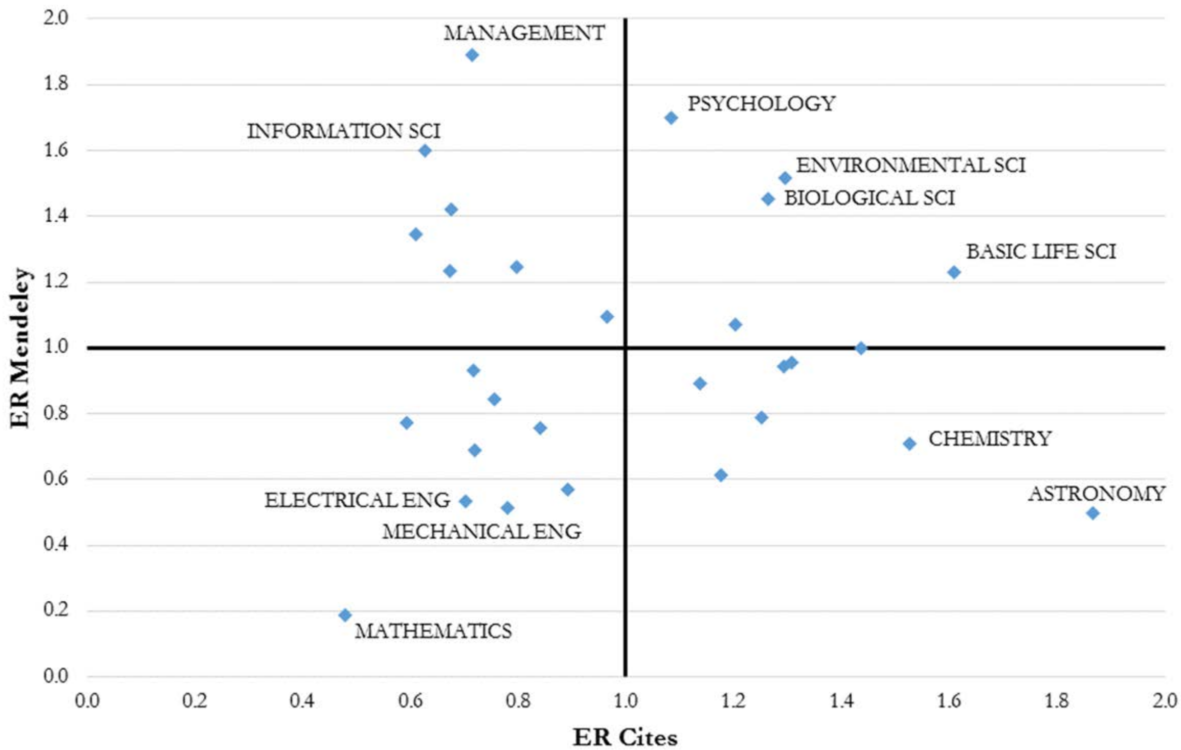
[4] For example, the first row in Table 4 indicates that 1.14 citations with a standard deviation of 0.08 for an article in *Agriculture and Food Science* between, approximately, the 50th and the 97th percentile of its citation distribution, are equivalent to one normalized citation for an article in that percentile interval in the all-fields case.

The ERs for most fields are reliable or fairly reliable in terms of their coefficient of variation, particularly regarding citations. The less reliable case is *Mathematics* both in terms of citations and Mendeley readership. There are fields with high ERs for citations and relatively low ones for readership and vice versa (Figure 5), this being obviously related to the higher (lower) densities of citation or readership that can be found across fields. Social Sciences fields such as *Management and Planning* have a high ERm for readership and a low ERc for citations. Fields like *Astronomy & Astrophysics* represent the contrary pattern, a high ERc for citations and a low ERm for readership. *Mathematics* is an example of low ERs in both metrics, while *Basic Life Sciences* is an example of high ERs in both metrics. These results align with previous results (Costas *et al.*, 2015a; Haunschild & Bornmann, 2016) on the existence of different rakings of disciplines based on the abundance/scarcity of one metric or the other.

Table 4. Field exchange rates over the percentile interval [50, 97]

FIELD	ERc	CV	ERm	CV
Agriculture and Food Science	1.14	0.07	0.89	0.04
Astronomy and Astrophysics	1.87	0.02	0.50	0.04
Basic Life Sciences	1.61	0.04	1.23	0.05
Basic Medical Sciences	1.31	0.06	0.96	0.02
Biological Sciences	1.26	0.03	1.45	0.02
Biomedical Sciences	1.44	0.05	1.00	0.02
Chemistry and Chemical Engineering	1.53	0.02	0.71	0.05
Civil Engineering and Construction	0.84	0.05	0.76	0.02
Clinical Medicine	1.25	0.03	0.79	0.04
Computer Sciences	0.72	0.08	0.93	0.08
Earth Sciences and Technology	1.20	0.04	1.07	0.02
Economics and Business	0.68	0.08	1.42	0.06
Educational Sciences	0.61	0.08	1.35	0.06
Electrical Engineering and Telecommunication	0.70	0.08	0.53	0.11
Energy Science and Technology	1.29	0.02	0.94	0.03
Environmental Sciences and Technology	1.29	0.03	1.51	0.02
General and Industrial Engineering	0.72	0.05	0.69	0.06
Health Sciences	0.96	0.05	1.09	0.10
Information and Communication Sciences	0.63	0.07	1.60	0.03
Instruments and Instrumentation	0.89	0.06	0.57	0.06
Law and Criminology	0.59	0.07	0.77	0.10
Management and Planning	0.71	0.06	1.89	0.03
Mathematics	0.48	0.10	0.19	0.28
Mechanical Engineering and Aerospace	0.78	0.05	0.51	0.04
Physics and Materials Science	1.18	0.06	0.61	0.09
Psychology	1.08	0.04	1.70	0.07
Social and Behavioral Sciences, Interdisciplinary	0.80	0.04	1.25	0.09
Sociology and Anthropology	0.67	0.07	1.23	0.05
Statistical Sciences	0.76	0.06	0.84	0.13

Figure 5. Correlation between the Exchange Rates of Citations (ER Cites) with. Exchange Rates of Mendeley readership (ER Mendeley)



Two strategies for field normalization

Field-normalization using exchange rates as normalization factors

As we know, the ERm for any field *f*, i.e., the e_f defined in equation 1, gives us the number of readership counts for an article in the interval [50, 97] in that field that are equivalent to one readership count in the all-fields case. Thus, a plausible normalization procedure is the following. If r_{fi} is the number of readership counts received by article *i* in field *f*, the ratio $r_{fi}* = r_{fi}/e_f$ is the normalized number of readership counts in the reference currency for that article. We denote by r_f* the normalized readership distribution for field *f*, and by $R* = \{r_f*, f = 1,…, 30\}$ the overall normalized readership distribution. Similarly, we denote by c_f* the normalized citation distribution for field *f*, and by $C* = \{c_f*, f = 1,…, 30\}$ the overall normalized citation distribution.

In our case, based on the ERs reported in Table 4, for example, a paper in *Educational Sciences* with 2 citations would be normalized to 2/0.61 = 3.28, while an *Astronomy and Astrophysics* paper with 3 citations would be normalized to 3/1.87=1.60. By dividing the two normalized values (3.28/1.60 = 2) we conclude that the *Educational Sciences* paper has an impact 2 times higher than the *Astronomy and Astrophysics* paper. Focusing on readership the two fields show an inverse pattern. In *Educational Sciences* 1.35 Mendeley readership would be exchanged by one item of normalized readership impact, while for *Astronomy & Astrophysics* it would require only 0.50 readership. The obvious reason is that Mendeley readership has a higher density in *Educational Sciences* than in *Astronomy and Astrophysics*, so that high values of readership in *Educational Sciences* will be equivalent to relatively lower levels of readership in *Astronomy and Astrophysics*.

There are two ways of assessing the consequences of field normalization: a graphical and a numerical way. In the graphical approach, the green lines in Figures 3 and 4 represent the expressions $I(\pi)$ after field normalization. Therefore, the difference between the blue curve (for raw data) and the green curve (for normalized data) illustrates the reduction of the effect on citation/readership inequality at each quantile π brought about by the procedure that uses exchange rates as normalization factors. Interestingly enough, the consequences of normalization for both metrics in the graphical approach are very similar.

The results in the numerical approach are presented in Table 5. In the citation case, the *IDCP* term is reduced from 0.04 to 0.008, a 82.5% difference. Of course, total citation inequality after normalization is also reduced. On balance, the *IDPC* term after normalization only represents 1.14% of total citation inequality –a considerable reduction from the 5.3% with the raw data. Note that in the last three percentiles and, above all, in the [1, 50) interval normalization results quickly deteriorate. The problem, of course, is that citation inequality due to different citation practices in these intervals is both high and extremely variable for different percentiles. As before, the impact of normalization in the Mendeley case is of the same order of magnitude: the *IDRP* term is reduced from 0.07 to 0.0013, an 85.5% difference, while the *IDRP* is reduced from 9.1% to 1.77% of total readership inequality.

Table 5. Overall citation/readership inequality decomposition after using exchange rates as normalization factors

	IDCP*	***I*(*C**)**	**100*[(1)/(2)]**
	(1)	**(2)**	**(3)**
CITATIONS			
All percentiles	0.0083	0.73	1.14
[1, 50)	0.0053		0.73
(50, 97]	0.0007		0.10
(97, 100]	0.0022		0.31
MENDELEY READERS	***IDRP****	***I*(*R**)**	**100*[(1)/(2)]**
All percentiles	0.013	0.75	1.77
[1, 50)	0.006		0.77
(50, 97]	0.001		0.23
(97, 100]	0.006		0.78

Field-normalization using field mean citations and readership counts as normalization factors

As is well known, the difficulties of comparing raw citation counts in different scientific fields have been traditionally confronted using field mean citations as normalization factors. Let us denote by c_f** and r_f** the normalized citation and readership distribution for field *f* in this case, and let $C^{**} = \{c_f^{**}, f = 1,\ldots, 30\}$ and $R^* = \{r_f^{**}, f = 1,\ldots, 30\}$ be the overall normalized citation and readership distributions.

The red lines in Figures 3 and 4 represent the expressions $I(\pi)$ after this type of field normalization. Clearly, the differences between the red and the green curves in both figures are truly minor. Therefore, according to the graphical approach, the consequences of the two normalization procedures are very similar indeed in both the citations and the readership cases.

The numerical results using mean citations and readership counts as normalization factors are presented in Table 6. After normalization, the *IDCP* and the *IDRP* terms are reduced by 80.0% and 81.4%, whereas these terms only represent 1.07% and 1.45% of overall citation and readership inequality. These are slightly better global results than in the previous normalization strategy. However, it should be noted that in the (50, 97] interval field exchange rates –defined precisely in such an interval– generate marginally better results than field means.

Table 6. Overall citation/readership inequality decomposition using field mean readership as normalization factors

	IDCP**	***I*(*C***)**	**100*[(1)/(2)]**
	(1)	**(2)**	**(3)**
CITATIONS			
All percentiles	0.0078	0.72	1.07
[1, 50)	0.0054		0.75
(50, 97]	0.0009		0.12
(97, 100]	0.0014		0.20
MENDELEY READERS	***IDRP*****	***I*(*R***)**	**100*[(1)/(2)]**
All percentiles	0.010	0.74	1.45
[1, 50)	0.006		0.85
(50, 97]	0.001		0.22
(97, 100]	0.003		0.38

In the citations case, the question is: how can this similarity of results for the two normalization procedures –observed also in Crespo *et al.* (2013)– be accounted for? The explanation is as follows. As documented in the CSS section, field mean citations are reached, on average at the 69 percentile with a small standard deviation, that is, clearly inside the (50, 97] interval used to estimate the ERc in Table 4. The relative constancy of the $I(\pi)$ expressions in that interval observed in Figure 3 indicates that field citation distributions appear to differ approximately by a set of scale factors in that interval. Thus, such scale factors should be well captured by any average-based measure of what takes place in that interval, such as the set of estimated ERc or the exchange factors implicit in the ratio of field mean citations and the mean citation in the all-sciences case. Naturally, the same explanation is valid for the readership case.

DISCUSSION AND CONCLUSIONS

The recent introduction and development of "altmetrics" has opened up the discussion about the hegemony of citation scores as the predominant source of scientific recognition. Mendeley readership have been shown to be the altmetric source that is most similar to citations counts (Maflahi & Thelwall, 2016), in contrast to other social media metrics that exhibit fundamental differences and much lower correlations with citations (Haustein *et al.*, 2015; Costas *et al.*, 2015a). As a result, there have been also technical proposals of field normalization of Mendeley readership mimicking that of citations (Haunschild & Bornmann, 2016). However, in-depth research about the differences and similarities between the distribution of the two metrics across fields, and empirical support for the suitability of field normalization of Mendeley readership are still lacking.

In this paper we have analyzed the shape of the distribution of these metrics across fields by using the CSS approach, we have shown that the Crespo *et al.* (2013) framework is applicable to the measurement of the effect on overall citation/readership inequality of the differences in citation /readership practices across fields, and we have shown two convenient average-based normalization procedures for overcoming the field dependence of both citations and Mendeley readership scores.

In line with previous research, we have confirmed that there are numeric differences in the density of the two metrics across disciplines. However, our CSS results show that the distributions of citations and Mendeley readership are strikingly similar across fields, exhibiting a very close skewed distribution for all fields of science – an aspect that has also been discussed by Thelwall & Wilson (2016) using a different approach.

Next, based on the similarity between readership distributions, we have shown that it is technically feasible to estimate well-behaved field ERs for readership over a wide range of intermediate quantiles, in a similar fashion to what has been done for citations. Such ERs can be used for comparing readership counts across fields, as well as reducing the effect on overall readership inequality of the idiosyncratic readership differences between fields. Finally, we have established that the standard procedure that uses mean readership scores as normalization factors achieves equally good results. Thus, the most important conclusion of the paper is that field normalization procedures for Mendeley readership can be fully applied in the same terms as for citations, empirically supporting the development of field-normalized indicators based on readership.

The possibility of using field-normalized indicators for Mendeley readership as is done for citations opens the door to new challenges, particularly regarding their potential comparability and interpretation (Haunschild & Bornmann, 2016). For example, what would happen if we find a paper (or a set of papers) for which the field normalized Mendeley readership is higher than its field normalized citations? What would happen when an institution has a stronger impact in terms of field-normalized Mendeley readership than in citations, or the other way around? These questions highlight the possibility that working with both indicators may lead to conflictive situations. In this case, the idea of a "currency conversion" between the two metrics could become a bone of contention in the determination of scientific recognition.

In the field of scientometrics the idea of establishing currency conversions among indicators is not new. Blaise Cronin, in an interview in 2012 (Sugimoto, 2012) suggested that "[t]*he idea of a symbolic capital currency convertor may not be all that far-fetched*" regarding the need for determining differential weightings of citations, acknowledgements and any other new metrics. Similarly, in the field of altmetrics Wouters & Costas (2012) suggested that "*inevitably the question of 'exchange rates' among all these [alt]metrics would arise …, bringing questions such as: how many 'reads' in Mendeley equate a citation?...*". From a more theoretical perspective the idea of "conversion rates" between different types of capital was already suggested by Bourdieu (1986). Thus, according to Bourdieu (1975) "[s]*cientific authority is … a particular kind of capital, which can be accumulated, transmitted, and even reconverted into other kinds of capital*", which is obtained based on the "distinctive value" of the work of scholars. Thus, when several indicators for capturing scientific recognition are considered, it is important to determine the "value" of the metrics that best capture the symbolic capital (i.e. recognition or esteem) of publications and authors.

In our case, one may wonder whether there could be some kind of "currency conversion" between our two metrics. For example, assuming that both metrics have equal merit, one may consider dividing the ER of citations (ERc) by the ER of Mendeley readership (ERm) for each field, as presented in Table 4, to obtain some sort of "currency conversion" rates from citations to Mendeley per field. However, would it be "valid" to directly compare the normalized values of citations and readership? To understand this question let's take the case of *Astronomy & Astrophysics*. By naïvely applying the ERs as currency convertors one could conclude that, given the scarcity of readership in this field, one Mendeley readership would be worth more than one citation in terms of normalized impact[5]. However, such interpretation obviously does not take into account the intrinsic value of the two "currencies" in terms of capturing "symbolic capital". For example, given the choice, probably most scientists would prefer to receive citations instead of (only) readership.

A plausible explanation for this potential higher esteem for citations over readership can be found in the framework of acts relating to research objects proposed by Haustein *et al.* (2016). In this framework, readership appears as acts of "access", related to a lower level of "engagement" of the users with the publications; while citations are seen as acts of "appraisal" related to a stronger engagement with the cited publication. Thus, taking engagement as a crude proxy of the potential worth attached to the metrics by different actors, it can be argued that these two metrics can be easily perceived to have different values in their ability to measure symbolic capital[6]. Therefore, making the direct comparison between the two highly problematic.

From another point of view, it might still be argued that more readers today may lead to more citations tomorrow (Zahedi *et al.*, 2017). It is also possible to maintain that highly cited papers would attract more Mendeley readership (Zahedi *et al*., 2017). Thus, before attempting any kind of

[5] The ERs would indeed suggest that 1 citation would only provide 1/1.87 = 0.53 of normalized citation impact, while 1 readership score would provide 1/0.50 = 2 of normalized readership impact.
[6] The different perceived values and esteem of new social media metrics in terms of symbolic capital are well illustrated in Desrochers *et al.* (2016).

specific currency conversion between the two metrics, it would be desirable to build a dynamic model in which the reverse causality between readership and citations is properly identified.

The above discussion clearly suggests that further research is necessary in order to disentangle the potential values of the two metrics (as well as any other new metric) in their ability to measure scientific recognition.

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APPENDIX

Table A. CSS results for citation distributions

Field	C1	C2	C3	%cits in C1	%cits in C2	%cits in C3
AGRICULTURE AND FOOD SCIENCE	67.4%	23.3%	9.3%	28.0%	34.8%	37.1%
ASTRONOMY AND ASTROPHYSICS	68.8%	22.2%	8.9%	27.0%	33.1%	39.9%
BASIC LIFE SCIENCES	71.1%	21.2%	7.6%	29.7%	32.0%	38.2%
BASIC MEDICAL SCIENCES	67.0%	23.8%	9.0%	27.7%	34.8%	37.5%
BIOLOGICAL SCIENCES	72.6%	20.7%	6.6%	30.0%	33.0%	36.9%
BIOMEDICAL SCIENCES	68.0%	22.5%	9.3%	27.7%	32.5%	39.7%
CHEMISTRY AND CHEMICAL ENGINEERING	69.9%	21.6%	8.5%	27.0%	32.7%	40.3%
CIVIL ENGINEERING AND CONSTRUCTION	67.5%	22.0%	10.5%	24.8%	33.5%	41.7%
CLINICAL MEDICINE	69.4%	22.4%	8.1%	25.4%	33.7%	40.6%
COMPUTER SCIENCES	73.3%	19.5%	7.0%	25.5%	33.3%	41.1%
EARTH SCIENCES AND TECHNOLOGY	65.9%	24.0%	10.1%	24.9%	34.1%	41.1%
ECONOMICS AND BUSINESS	69.3%	21.4%	9.2%	22.6%	32.5%	44.8%
EDUCATIONAL SCIENCES	71.8%	19.3%	8.7%	26.6%	32.4%	40.7%
ELECTRICAL ENGINEERING AND TELECOMMUNICATION	67.9%	22.3%	9.7%	21.1%	33.2%	45.5%
ENERGY SCIENCE AND TECHNOLOGY	68.0%	23.4%	8.5%	23.6%	34.8%	41.5%
ENVIRONMENTAL SCIENCES AND TECHNOLOGY	67.8%	23.5%	8.7%	26.4%	34.3%	39.3%
GENERAL AND INDUSTRIAL ENGINEERING	66.4%	23.1%	10.4%	22.9%	34.1%	42.8%
HEALTH SCIENCES	68.5%	21.8%	9.5%	27.3%	32.9%	39.6%
INFORMATION AND COMMUNICATION SCIENCES	70.8%	21.6%	7.5%	24.6%	34.9%	40.4%
INSTRUMENTS AND INSTRUMENTATION	71.7%	20.4%	7.8%	26.0%	33.2%	40.7%
LAW AND CRIMINOLOGY	64.2%	24.2%	11.5%	19.5%	34.9%	45.4%
MANAGEMENT AND PLANNING	67.2%	23.2%	9.5%	21.8%	34.9%	43.2%
MATHEMATICS	72.3%	20.3%	7.4%	22.7%	34.8%	42.5%
MECHANICAL ENGINEERING AND AEROSPACE	70.3%	20.6%	9.1%	26.9%	33.6%	39.5%
PHYSICS AND MATERIALS SCIENCE	71.6%	20.8%	7.5%	25.3%	32.9%	41.7%
PSYCHOLOGY	69.4%	21.1%	9.4%	28.2%	32.6%	39.1%
SOCIAL AND BEHAVIORAL SCIENCES, INTERDISCIPLINARY	69.2%	21.4%	9.4%	26.6%	34.4%	38.9%
SOCIOLOGY AND ANTHROPOLOGY	68.7%	22.3%	8.9%	22.1%	34.3%	43.4%
STATISTICAL SCIENCES	71.8%	21.6%	6.5%	24.0%	34.1%	41.7%
Average	69.2%	21.9%	8.8%	25.4%	33.7%	40.8%
Standard deviation	2.2	1.3	1.2	2.6	0.9	2.3
CV	0.03	0.06	0.13	0.10	0.03	0.06

Table B. CSS results for readership distributions

Field	C1	C2	C3	%readership in C1	%readership in C2	%readership in C3
AGRICULTURE AND FOOD SCIENCE	67.8%	23.3%	9.0%	27.0%	34.4%	38.7%
ASTRONOMY AND ASTROPHYSICS	68.1%	22.2%	9.6%	25.8%	33.1%	41.1%
BASIC LIFE SCIENCES	72.6%	20.4%	7.0%	28.0%	31.3%	40.8%
BASIC MEDICAL SCIENCES	68.5%	22.4%	9.2%	27.3%	33.5%	39.3%
BIOLOGICAL SCIENCES	71.7%	20.8%	7.5%	28.2%	32.1%	39.8%
BIOMEDICAL SCIENCES	70.4%	21.9%	7.7%	27.3%	32.9%	39.9%
CHEMISTRY AND CHEMICAL ENGINEERING	70.1%	21.8%	8.2%	24.8%	33.9%	41.4%
CIVIL ENGINEERING AND CONSTRUCTION	67.3%	23.0%	9.6%	24.9%	33.8%	41.3%
CLINICAL MEDICINE	69.0%	22.8%	8.3%	27.7%	34.7%	37.8%
COMPUTER SCIENCES	70.4%	21.1%	8.6%	23.6%	32.9%	43.6%
EARTH SCIENCES AND TECHNOLOGY	69.8%	21.8%	8.4%	27.5%	33.2%	39.3%
ECONOMICS AND BUSINESS	71.2%	19.9%	8.9%	27.2%	31.6%	41.3%
EDUCATIONAL SCIENCES	67.8%	22.4%	9.9%	30.7%	32.8%	36.9%
ELECTRICAL ENGINEERING AND TELECOMMUNICATION	71.8%	20.4%	7.8%	23.1%	33.3%	43.7%
ENERGY SCIENCE AND TECHNOLOGY	69.0%	21.6%	9.4%	24.9%	33.7%	41.4%
ENVIRONMENTAL SCIENCES AND TECHNOLOGY	70.4%	20.8%	8.7%	27.6%	32.0%	40.5%
GENERAL AND INDUSTRIAL ENGINEERING	70.8%	20.6%	8.6%	24.9%	33.4%	41.8%
HEALTH SCIENCES	65.0%	24.7%	10.3%	29.5%	34.3%	36.3%
INFORMATION AND COMMUNICATION SCIENCES	67.8%	22.0%	10.2%	29.5%	31.7%	39.0%
INSTRUMENTS AND INSTRUMENTATION	73.0%	20.3%	6.6%	26.0%	32.9%	41.2%
LAW AND CRIMINOLOGY	64.7%	25.1%	10.4%	28.4%	34.9%	37.2%
MANAGEMENT AND PLANNING	68.5%	21.4%	10.1%	26.8%	32.7%	40.6%
MATHEMATICS	78.6%	16.4%	5.0%	20.0%	31.5%	48.6%
MECHANICAL ENGINEERING AND AEROSPACE	67.9%	23.1%	9.0%	23.0%	35.1%	42.0%
PHYSICS AND MATERIALS SCIENCE	71.2%	21.2%	7.6%	22.9%	33.9%	43.3%
PSYCHOLOGY	68.6%	22.1%	9.3%	31.9%	31.8%	36.4%
SOCIAL AND BEHAVIORAL SCIENCES, INTERDISCIPLINARY	65.5%	24.1%	10.5%	30.0%	33.4%	36.7%
SOCIOLOGY AND ANTHROPOLOGY	69.4%	21.8%	8.8%	30.3%	32.1%	37.7%
STATISTICAL SCIENCES	73.3%	19.6%	7.1%	23.4%	32.6%	44.1%
Average	69.7%	21.7%	8.7%	26.6%	33.1%	40.4%
Standard deviation	2.8	1.7	1.3	2.8	1.1	2.7
CV	0.04	0.08	0.10	0.10	0.03	0.07