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Consensus formation in science modeled by aggregated bibliographic coupling

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ABSTRACT

The level of consensus in science has traditionally been measured by a number of different methods. The variety is important as each method measures different aspects of science and consensus. Citation analytical studies have previously measured the level of consensus using the scientific journal as their unit of analysis. To produce a more fine grained citation analysis one needs to study consensus formation on an even more detailed level – i.e. the scientific document or article. To do so, we have developed a new technique that measures consensus by aggregated bibliographic couplings (ABC) between documents. The advantages of the ABC-technique are demonstrated in a study of two selected disciplines in which the levels of consensus are measured using the proposed technique.

1. Introduction

There are many ways to classify the sciences. One, that is frequently seen, is the distinction between *hard sciences* and *soft sciences*. Houser (1986) identifies Warren O. Hagstom's book '*The Scientific Community*' from 1965 as the first work in which the hard science-soft science terminology is used (Hagstrom, 1965). Yet, the most famous example in our field is probably Derek J. de Solla Price's '*Citation Measures of Hard Science, Soft Science, Technology, and Nonscience*' (Price, 1970). The idea about a hierarchy of the sciences is of course much older. Cole (1992) traces it back at least to Auguste Comte (1798–1857) who ranked the sciences according to ascending complexity (mathematics, astronomy, physics, chemistry, biology, and sociology). Nevertheless, the search for a hierarchy of the sciences is perhaps misguided.[1] Most (if not all) disciplines tend to have hard as well as soft sides, and the "average" hardness or softness of a discipline may thus be a feeble measure. A recent paper on the temporal structure of scientific consensus formation reaches a similar conclusion. The authors (Shwed & Bearman, 2010) argue that science advances around sub- and multi-disciplinary puzzles, and consequently that consensus formation takes place at sub- and multi-disciplinary level. Investigating the level of hardness/softness *within* different disciplines seems therefore to be a more fruitful way to go.

Regardless of the focal point, measuring the hardness/softness of science requires an operational definition of the hard/soft concept. It is generally established that assessing the level of agreement within a scientific domain is the best measure for the hard/soft dichotomy:

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[1] Houser (1986:367) goes as far as calling the hard science-soft science notion a myth.

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> "For the past two hundred years it has been assumed that there are differences among the sciences in levels of cognitive consensus. Highly codified fields such as physics are assumed to have substantially higher levels of agreement than are less codified fields such as sociology" (Cole, 1992:108).

Contemporary researchers have produced different rankings based on various consensus measures (see Shwed & Bearman, 2010:819–820 for an overview). The aim of this paper is consequently not to introduce a single measure that can fully replace all other methods, but instead to present and discuss an additional measure that may prove to offer opportunities for a more fine grained analysis than the existing citation based measures. The measure is based on calculations of the aggregated bibliographic coupling strength of documents and their bibliographic couplings. We have therefore chosen to name it *ABC* in short for *Aggregated Bibliographic Coupling*. Documents are said to be bibliographically coupled if they share one or more bibliographic references. The concept of bibliographic coupling was introduced by Kessler (1963) who demonstrated the existence of the phenomenon and argued for its usefulness as an indicator of subject relatedness. However, as noted by Glänzel and Czerwon (1996) and De Bellis (2009) the technique lived a relatively quiet life until the 1990s when bibliometricians began to employ it for identifying and mapping clusters of subject-related documents (e.g., Ahlgren & Jarneving, 2008; Glänzel & Czerwon, 1996; Jarneving, 2007). As noted above, we believe that the bibliographic coupling technique has another promising potential – namely as a measure of the level of consensus in science. We will demonstrate this by employing the ABC-technique to the study of consensus within two disciplines (physics and psychology). By comparing the results with results from previous studies, we will show that the ABC-technique produces comparable results on field and journal level. As the ABC-technique may be employed on article level as well, it can hopefully contribute to enrich the hard/soft discussion.

The paper is structured as follows. The next section introduces two related citation based measures of consensus, followed by a section explaining the ABC-technique. It is followed by a methods section in which we outline the procedures employed for our studies of psychology and physics. In the results section we present the results and compare our findings with previous studies of the level of consensus within psychology and physics. The paper ends with a brief discussion and suggestions for future work in this area.

2. Related citation based measures of consensus

Price (1970) presents a number of quantitative means to distinguish between hard science, soft science and non-science. He argues for the use of the immediacy effect which is "a special hyperactivity of the rather recent literature which was still, so to speak, at the research front" (Price, 1970:9). The immediacy effect can be measured by Price's index, which is defined as the proportion of references in the scientific literature that are to the last five years of literature. Price (1970:10) suggests that a Price's Index value between 75 and 80 can be interpreted as the research front. Price finds that the hierarchy of the Price Index corresponds with "what we intuit as hard science, soft science as we descend the scale." (Price, 1970:12). Moed (1989) has computed Price's Index values for a number of fields and concludes that

> "Interpreted in terms of Price' s theory on knowledge growth, our findings suggest that within the natural and life sciences, and even within a discipline such as biochemistry, different processes of knowledge growth may occur. Apparently, in some subfields the mode of utilization of knowledge seems to be more 'archival', while other subfields tend to build more rapidly upon highly specialized segments of recent literature" (Moed, 1989:482).

Although, the ranking of journals by Price may correspond to what we intuit as hard science and soft science, the results by Tang (2008) do not necessarily support this claim. Tang (2008) has extended the work by Price by including monographs and finds that including monographs in the analysis yields results that in some ways are consistent with the previous findings of around 50% recent literature for science. On the other hand, he finds that the monographs in religion and history have a higher immediacy effect than the estimated 21% from previous findings.

A different approach for analysis of consensus is suggested by Cole, Cole, and Dietrich (1978) who analyse the distribution of references in 1971 in 108 scientific journals. Cole (1983) argues that

> "[a] more concrete, measure of consensus is the distribution of citations in a scientific journal. In fields characterized by a high level of intellectual agreement, we would expect to find a heavy concentration of references to a relatively small number of papers and authors. The distribution of references in fields characterized by lack of agreement should more closely approximate a random distribution".

A Gini coefficient is computed for each journal. They find relatively small differences in the mean Gini coefficients of the various fields, whereas they find considerable differences within fields. An overview of the results is reproduced from Cole (1983:121) in Table 1.

As noted by Cole (1983) the variation between journals is anything but insignificant. Consequently, we are determined to analyse the level of variance within journals. However, the Cole approach is not suitable for single articles. We have therefore developed a new technique.

Table 1
Concentration of citations to research articles in selected fields. Reproduced from Cole (1983:121).

Gini coefficients			
Field	N journals	Mean	Range
Biochemistry	10	.21	.05–.34
Chemistry	12	.15	.06–.27
Geology	7	.10	.04–.23
Mathematics	6	.09	.06–.13
Physics	10	.18	.06–.35
Psychology	8	.16	.05–.29
Sociology	7	.09	.05–.11

3. The ABC technique

Measuring consensus by distribution of bibliographic couplings in scientific journals forms the basis of the present study. Documents are bibliographically coupled if they share one or more bibliographic references. An increase in the number of shared references implies an increase in consensus on what publications to cite. In fields characterized by a high level of intellectual agreement, we would expect to find a high number of shared references. The number of shared references in fields characterized by lack of agreement should be relatively lower. Consequently, aggregating the number of shared references for each bibliographically coupled document provides information on the level of consensus within the field of the document. Bibliographically coupled articles are determined for every article included in the study. Web of Science provides information on the number of related articles (articles that are bibliographically coupled with the article in our sample) and the number of shared references. The ranked list of occurrences of shared references forms the basis for calculating the degree of diversity. The following is two examples of the data collection process. Article A which has 47 references is looked up in Web of Science and 6009 related records are found. Article B which has 41 references and 7548 related records. The bibliographic couplings can be seen in Table 2.

A quick look at Table 2 reveals that article A and about 22% of its related records have more than one shared reference. Article B only shares more than one reference with about 3% cent of its related records. Consequently, it would seem that the field of article A is characterized by a higher level of consensus on which articles to cite. However, a quick look at a table is not sufficient for the analysis – diversity or consensus has to be quantified. Diversification can be measured as the inverse of concentration (Foldvary, 2006). Gini measures give more importance to small units; Herfindahl measures emphasize the importance of large units, but the two measures supplement each other well (Ceapraz, 2008). Cole (1983:126) uses the Gini coefficient G which is a measure typically used to measure inequality (for recent examples within this field see, e.g. Burrell, 2008; Chiang, Huang, & Huang, 2009; Huang, Shen, Chiang, & Lin, 2007). At pure equality, G = 0, and at pure inequality, G = 1. Measures of inequality are closely related to measures of concentration and diversification. The Gini coefficient (or Gini ratio) is a summary statistic of the Lorenz curve and a measure of inequality in a population. The Lorenz curve plots the proportion of the total income of the population (y axis) that is cumulatively earned by the bottom x% of the population. This curve assumes that each element has the same contribution to the total summation of the values of a variable and is compared to a ranked empirical distribution. Graphically, the Gini coefficient represents the area between the Lorenz curve and the line of perfect equality relative to the area enclosed by the triangle defined by the line of perfect equality and the line of perfect inequality. The Gini coefficient can be calculated "from unordered size data as the relative mean difference, implying that the mean of the difference between every possible pair of individuals is divided by the mean size" (Damgaard, 2010). The examples in Table 2 results in Gini coefficients of 0.22 for article A and 0.03 for article B. To characterize a field or a journal mean or median values of the Gini coefficients can be computed for the articles included in the sample.

Table 2
Examples of data collection.

Examples of related records and their bibliographic coupling strength			
Article A		Article B	
N shared references	N related records	N shared references	N related records
1	4649	1	7343
2	911	2	155
3	244	3	34
4	114	4	12
5	46	5	1
6	28	6	3
7	6		
8	6		
9	1		
10	2		
11	2		

Table 3
List of journals and the disciplines they represent.

	Articles in 2009
Physics	
Journal of Applied Physics	4253
Journal of Physics (C)[a]	1529
Physical Review Letters	3414
Physical Review A	3026
Journal of Geophysical Research[b]	696
Psychology	
Behavioral Neuroscience	58
Journal of Experimental Psychology: Animal Behavior Processes	50
Journal of Experimental Psychology: General	28
Developmental Psychology	135
Journal of Comparative Psychology	45
Journal of Abnormal Psychology	69
Journal of Personality and Social Psychology	138
Journal of Consulting and Clinical Psychology	103
Journal of Educational Psychology	63
Journal of Counseling Psychology	48

[a] The title of the journal was from 1968 to 1988 Journal of Physics C: Solid State Physics. The journal is now published under the title: Journal of Physics: Condensed Matter. This journal was formed by a merger of Journal of Physics C: Solid State Physics (1968–1988) and Journal of Physics F: Metal Physics (1971–1988). This publication is also derived from the following former titles, either partially, or from a past, total merger: Metal Physics (1970); Proceedings of the Physical Society (1958–1967); Proceedings of the Physical Society. Section A (1949–1957); Proceedings of the Physical Society. Section B (1949–1957); Proceedings of the Physical Society (1926–1948); Proceedings of the Physical Society (1874–1925); and Transactions of the Optical Society (1899–1931).

[b] In 1980, three specialized sections were established: A: Space Physics, B: Solid Earth, and C: Oceans. Subsequently, further sections have been added: D: Atmospheres in 1984, E: Planets in 1991, F: Earth Surface in 2003, and G: Biogeosciences in 2005.

4. Methods

In outline, the method adopted for this study was to:

(a) Devise a sampling frame.
(b) Obtain details on the bibliographic coupling strength of the selected papers and their references.
(c) Compute Gini values of bibliographic couplings.

First, a number of disciplines had to be selected and preferably they should illustrate a relatively soft as well as a relatively hard discipline. We had originally intended to include the same journals as Cole et al. (1978) did in their study. However, as they only provide examples of the included journals and thus not the complete list of journals, it could not form the basis of our study.

Instead, we chose to limit our study to two disciplines: Physics and psychology. In both cases we can obtain results from studies of hardness which can be interesting for comparative analyses. The physics journals are selected on the basis of the included physics journals in the study reported by Cleveland (1984). Cleveland provides a figure (p. 264) in which hardness of the included journals are presented. Exact values of hardness are not listed but they can be approximated from the figure. Smith, Best, Stubbs, Johnson, and Archibald (2000) calculates hardness of ten psychology journals. The same journals were chosen to represent the discipline of psychology in our study. Consequently, in the case of the psychology journals we also have the opportunity to analyse the relation between hardness and degree of consensus.

An overview of the included disciplines, the journals representing them, and the number of articles published in these journals in 2009 is available in Table 3.

Secondly, searches were conducted using the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI) available on the Web of Science. From each journal a random sample of 15 research articles published in 2009 were selected for analysis. The journals in our study publish from 28 to 4253 articles in 2009 and consequently, the sample size varies.[2] These articles were looked up individually and related records retrieved. Each article is entered into the dataset with the following information: number of references (this information enables us to control for any relation between the number of references and the degree of consensus), information that identify the article (e.g. volume, page number, identification number), and the distribution of the number of shared references. The data have been analysed using SPSS and the results are presented in the form of graphs.

[2] Due to the substantial differences in the number of publications and exploratory character of the study a representative sample of each journal was not prioritized.

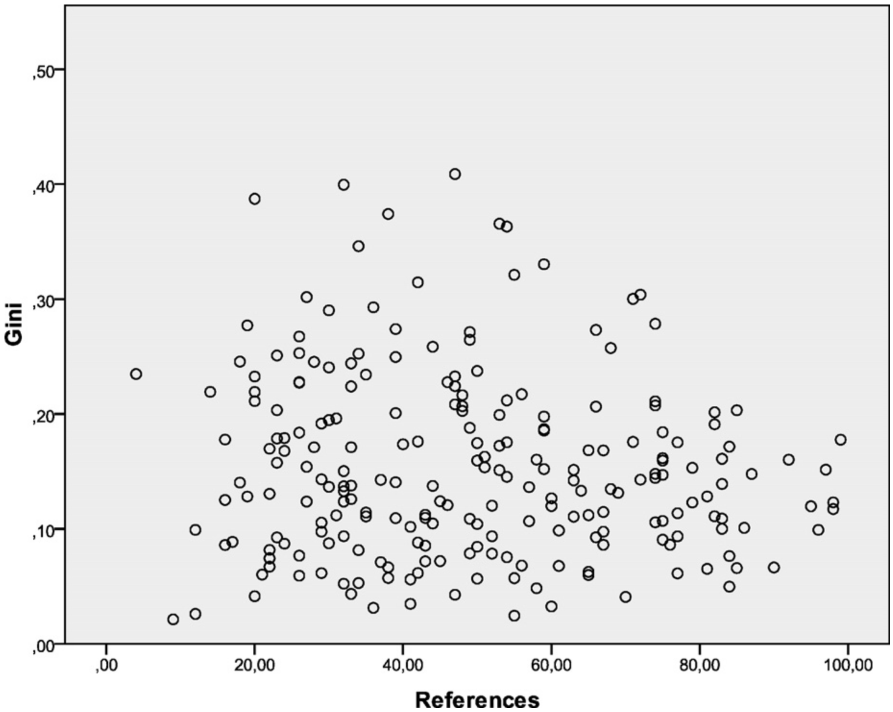

Fig. 1. Number of references and ABC Gini coefficients.

5. Results

Before turning to the results it is worth analysing if Gini coefficients resulting from the ABC technique can be correlated with length of reference lists. Should high ABC Gini values be correlated with high numbers of references there is no need for further analysis, however, as illustrated by Fig. 1 this is not the case.

There is clearly no correlation which is also supported by a linear regression. The *p*-value of the variable "number of references" is .129 which gives us cause for further analysis.

Using the method suggested by Cole as well as the ABC-method we have computed the Gini values for the same set of journals. First of all, any potential correlation between the two measures of consensus is analysed. Fig. 2 illustrates that the two measures produce comparable although not similar results. The ABC method generally produces lower Gini coefficients but there is not a 100% correlation suggesting that the two methods measure different aspects of consensus.

As stated earlier the method for calculating consensus suggested by Cole can only be computed on journal level and/or on the level of fields by computing a mean value. However, the median and mean values cannot provide us with a clear picture of the distribution of Gini coefficients within physics and psychology neither on discipline level nor on journal level. Fig. 3 provides illustrations of the median Gini coefficients of each physics journal. The journals are sorted according to hardness using Cleveland's (1984) classification. The error bars represent the 95% confidence interval.[3] In this case we may calculate that the true (i.e., population) median Gini of the journal with a hardness of .20 is between .06 and .23 with 95% confidence.

The figure does not suggest a linear correlation between hardness and consensus, although it can be difficult to determine with the relatively low number of journals in the data set.

Fig. 4 provides illustrations of the mean and median Gini coefficients of each psychology journal. The journals are again sorted according to hardness, but it should be noted that hardness is not measured using the same scale as in the case of the physics journals (see Smith et al., 2000). The error bars represent the 95% confidence interval.

The figure suggests a positive correlation and a linear regression confirms the correlation (*p*-value of .000). Consequently, psychology can be characterized as a field where consensus increases as we move from soft to hard journals.

[3] Using the concept of the confidence interval, sample information can be used to identify a range within which a given population parameter is expected to fall with a given level of confidence. To make inferences from the data (i.e., to make a judgment whether the journals are significantly different, or whether the differences might just be due to random fluctuation or chance) confidence intervals can be used. The error bars are not effective for assessing the statistical significance of the differences in medians but the 95% confidence indicates that, if this confidence interval method was repeated many times with different randomly selected samples, 95% of the confidence intervals so estimated would contain the true median Gini coefficient. Five percent of the time, the true median would lie outside of the confidence interval. (e.g. Egghe & Rousseau, 1990:47; Payton, Greenstone, & Schenker, 2003; Smithson, 2003).

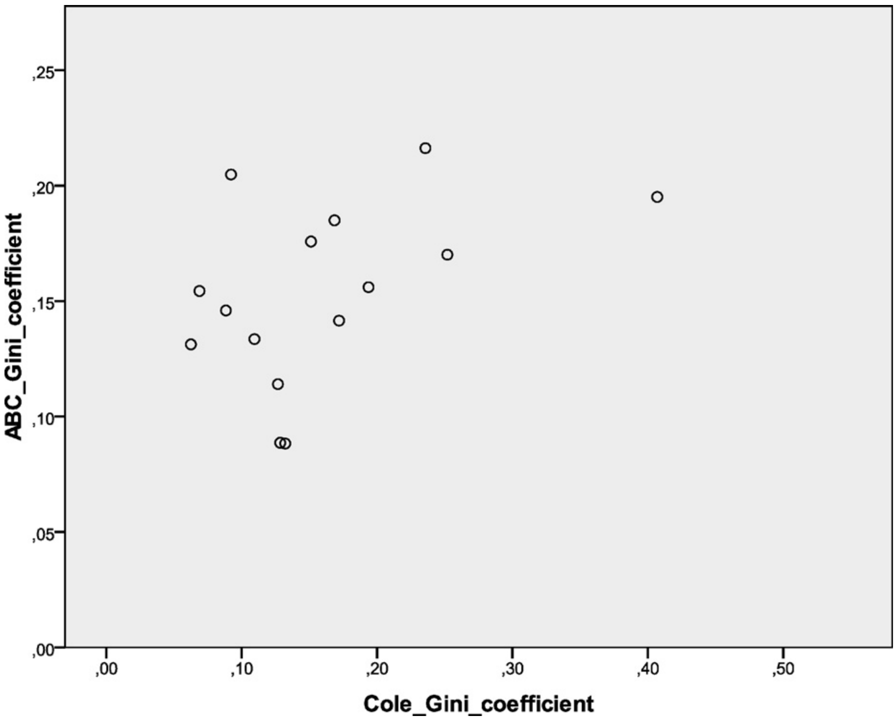

Fig. 2. ABC Gini coefficients and Cole Gini coefficients.

Fig. 5 is an illustration of the median Gini coefficients of the two disciplines journal. The error bars represent the 95% confidence interval.

Using the ABC-technique we find that psychology journals are generally characterized by a lower degree of consensus than physics journals. Physics is consequently, a field characterized by a higher level of intellectual agreement, as we find

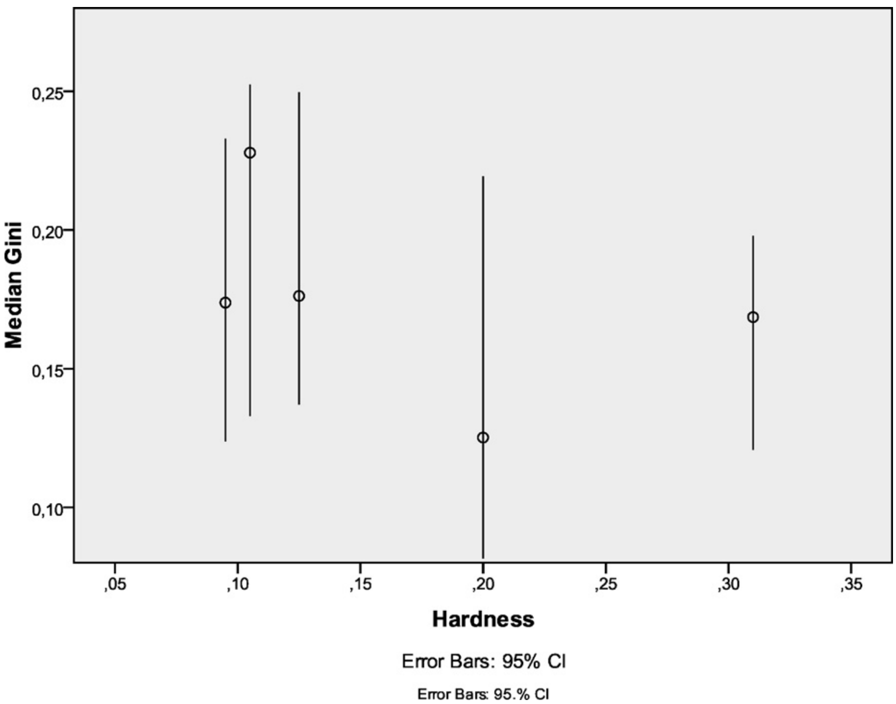

Fig. 3. Median physics journals Gini coefficients and hardness. The error bars represent the 95% confidence interval.

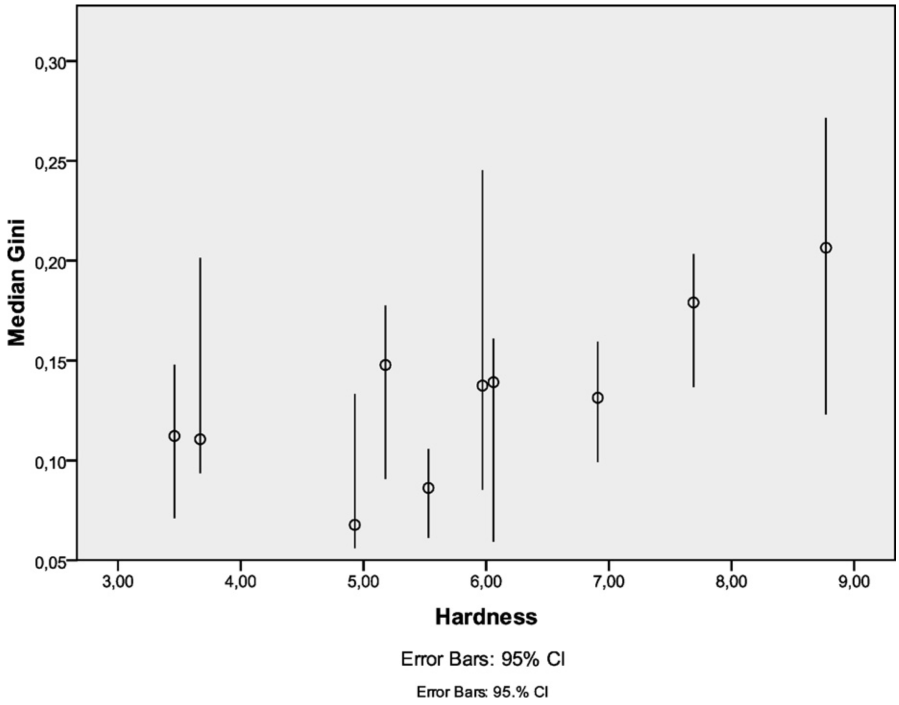

Fig. 4. Median psychology journals Gini coefficients and hardness. The error bars represent the 95% confidence interval.

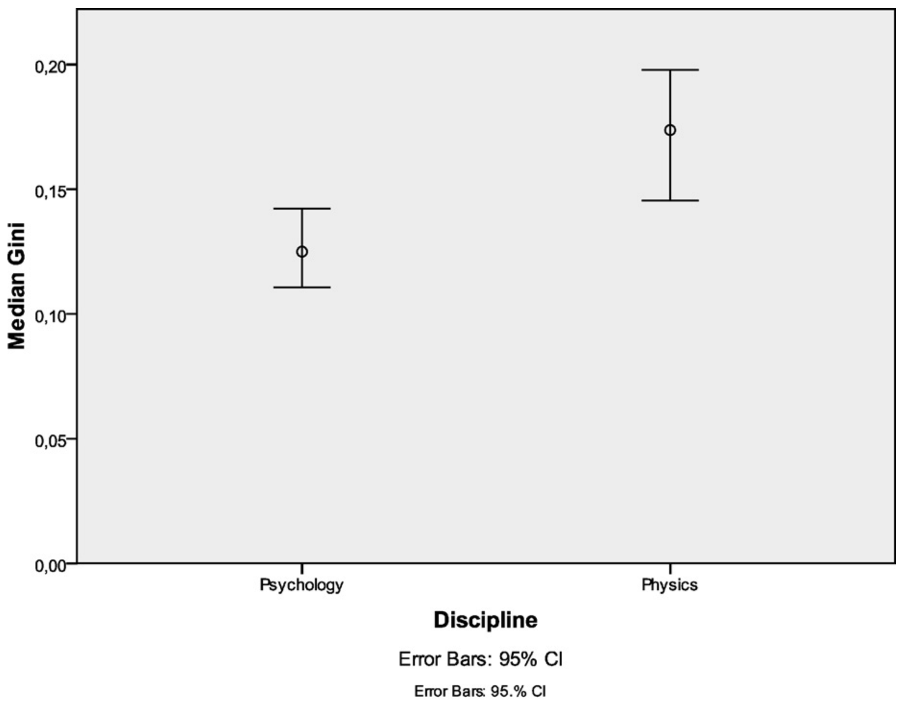

Fig. 5. Median physics and psychology discipline Gini coefficients. The error bars represent the 95% confidence interval.

a high number of shared references. Psychology, on the other hand, is a field characterized by lower level of agreement as the number of shared references is relatively lower. Aggregating the number of shared references for each bibliographically coupled document provides information on the level of consensus within the field of the document.

6. Discussion and conclusion

Sociologists and others are regularly having discussions about the consensus level in science. Two of the most active debaters on this topic have undoubtedly been the sociologists Stephen Cole and Lowell L. Hargens. The heart of their controversy has been the question about the level of consensus at the research front. Cole (1992:15) makes a distinction between the research frontier and the core:

> "The core consists of a small set of theories, analytic techniques, and facts which represent the given at any particular point in time.
> The research frontier is where all new knowledge is produced".

Cole argues that it is necessary to make this distinction because the social character of knowledge differs dramatically between the two components. "By definition there is a high level of agreement on core knowledge" (Cole, 1992:19). Contrary, "the level of cognitive consensus at the frontier is relatively low in all scientific fields" (Cole, 1992:19). As noted by Cole (1992) himself, this position is at odds with positivists, Kuhn, and most traditional sociologists of science. Hargens is one of the sociologists of science who have gone against Cole on this topic. Over the years, he has published a number of empirical studies dealing with the question about consensus levels at the research frontier (e.g., Hargens & Hagstrom, 1982; Hargens, 1988b, 2000). Hargens distinguish between foundational and current scholarship, and believes contrary to Cole that the level of consensus in current scholarship differs from discipline to discipline. In some disciplines the level of consensus in current scholarship is high. In other disciplines the level is low. The results of his reference network analysis (Hargens, 2000) seem to confirm this.[4]

Hargens' study from 1988 on scholarly consensus and journal rejection rates was followed by a discussion between Cole (and colleagues) and himself (Cole, Cole, & Simon, 1988; Hargens, 1988a). A key question in this discussion was whether journal rejection rates are related to disciplinary variation in consensus. Similarly one could discuss whether the distribution of references and citations are related to disciplinary variation in consensus. Cole and Hargens have both produced empirical support for their beliefs using citation analysis as their method. Using the journal as their unit of analysis, Cole et al. (1978) found that the concentration of references differed significantly between journals in all fields. Yet, only small differences were found between disciplines. Using the journals as the unit of analysis has a potential problem. It reduces the operationalisation of a discipline to one or a few journals. When counting the level of consensus by bibliographic coupling on the journal level, the researcher only finds out how often articles in this particular journal are bibliographically coupled with each other. Hargens (2000) faces a similar problem. In his study he investigated two prototypical disciplinary modes of literature use: Authors in the first mode focus on recently published literature, incorporating past work without acknowledging original sources. Authors in the second mode tend to ignore recent work in favor of foundational texts. Applying reference network analysis to compare seven research areas, he found that reference patterns vary greatly across research areas and he concludes that the differences in part is caused by differences in how scholars use the work by other scholars. Although his level of analysis is the research article, his study is limited by the fact that he only investigated the reference network in limited bibliographies. Thus, for example, in his study of the research area Celestrial masers (broader discipline: Astronomy) he based his investigation on 384 papers and the references between the same 384. Like in the study by Cole et al. (1978), references to papers outside the predefined bibliography were not examined. Whether such limited bibliographies reduce the validity of claims regarding consensus in science is an open question. Among bibliometricians it is, however, well known that the related subject of database coverage plays a key role in most bibliometric studies (see Frandsen & Nicolaisen, 2008 for an overview). We therefore invented an alternative method for studying the consensus in science question by citation analysis. The ABC-technique takes the research article as its unit of analysis and counts the number of bibliographic couplings between the individual research article and all other documents indexed in Web of Science. Moreover, it corrects for number of references in the source article. Of course the ABC-technique is also based on a predefined bibliography (Web of Science), but it is arguably a much larger one than the ones defined and used by Cole and Hargens.

Applying the ABC-technique on research articles from the fields of physics and psychology we are able to report that:

1. The number of references is not correlated with Gini-values indicating that a small number of references in an article does not imply a greater level of consensus.
2. The results indicate that there generally seems to be a higher degree of consensus in current scholarship in physics than in psychology.
3. There is great variation within disciplines (there is no such thing as the typical journal).
4. There is a great variation within journals (there is no such thing as the typical article).

[4] Although the variation is inconsistent with the pattern expected of a simple physical sciences – behavioral sciences – humanities dimension.

These results alone are of course not the final verdict in the consensus in science trial. They represent only the conditions in a selected sample of articles from two disciplines. Further studies are clearly needed before any stronger conclusions may be drawn. Preferably, such studies should be based on a variety of methods including citation analysis. Citation analytical studies could benefit from implementing the ABC-technique as it produces more fine grained results compared to previous citation analytical techniques used for measuring consensus.

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