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Understanding the impact change of a highly cited article: a content-based citation analysis

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Abstract Researchers tend to cite highly cited articles, but how these highly cited articles influence the citing articles has been underexplored. This paper investigates how one highly cited essay, Hirsch's "h-index" article (H-article) published in 2005, has been cited by other articles. Content-based citation analysis is applied to trace the dynamics of the article's impact changes from 2006 to 2014. The findings confirm that citation context captures the changing impact of the H-article over time in several ways. In the first two years, average citation mention of H-article increased, yet continued to decline with fluctuation until 2014. In contrast with citation mention, average citation count stayed the same. The distribution of citation location over time also indicates three phases of the H-article "Discussion," "Reputation," and "Adoption" we propose in this study. Based on their locations in the citing articles and their roles in different periods, topics of citation context shifted gradually when an increasing number of other articles were co-mentioned with the H-article in the same sentences. These outcomes show that the impact of the H-article manifests in various ways within the content of these citing articles that continued to shift in nine years, data that is not captured by traditional means of citation analysis that do not weigh citation impacts over time.

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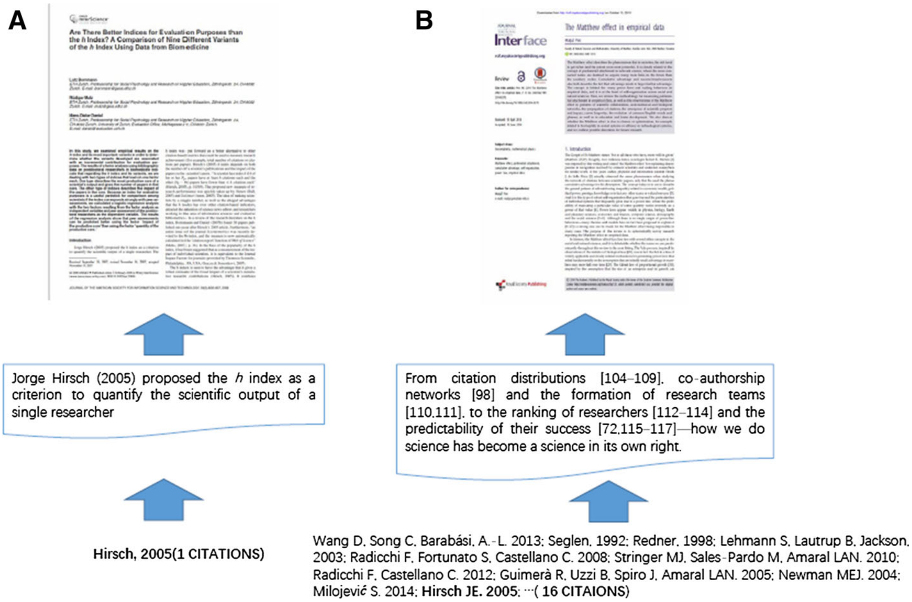
Introduction

Citation count has been used as the de facto standard to measure the impact of an article, a researcher, or an institution. But how a highly cited article impacts a field and how these influences change over time has not been well explored. It is important to understand how a paper's impact grows, diffuses, and fades so as to: (1) facilitate scholarly communication and understanding of research obsolescence trends; (2) detect impact changes in different domains and factors of influence; and (3) differentiate the impact of papers even when they have roughly the same number of citations. Using citation count alone to measure the impact of a paper is a limited approach, in that it ignores impact changes and cited articles' unequal contributions to citing articles, especially relevant for highly cited articles (MacRoberts and MacRoberts 1989; Voos and Dagaev 1976; Aksnes 2003). Researches on citation contribution (Cano 1989; Case and Higgins 2000; Garfield 1964; Lipetz 1965; Moravcsik and Murugesan 1975; Voos and Dagaev 1976) have found that perceived contributions of an article vary within the text of citing articles. Lipetz (1965), for example, presented 29 categories of citation motivations in physics literature. As different perceived "contributions" in this sense may imply varied impacts of the cited article, this finding only confirms that it is problematic to assume that all citations in an article are interpreted by the citing article in the same manner. Impact decay of articles over time has also been investigated for decades. As scientific knowledge and contributions are dynamic and quickly changing in light of new discoveries, it is important to acknowledge nuanced factors of an article's influence, including its changing impact over time. Furthermore, numerous studies (Cano 1989; Moravcsik and Murugesan 1975; Small 1978; Voos and Dagaev 1976) confirm that analyzing citation context can help differentiate various motivations and functions of citations. So how, where, and how many times an article in positioned in relation to other works is a relevant factor to consider when exploring its potential impact, including its impact decay over time. We choose Hirsch's (2005) highly cited article, "An index to quantify an individual's scientific research output" to illustrate this issue of citation change over a nine-year period (where the article is referred as "H-article" and the index as "h-index" hereafter). Figure 1 shows the citation patterns of two articles published in 2008 (Article A) and 2014 (Article B) that cite the H-article to support their arguments (Case and Higgins 2000). In the citing sentence of Article A where the H-article is mentioned, no other article is co-mentioned, while in the citing sentence of Article B, the H-article is co-mentioned together with 15 other articles. We can therefore assume that the H-article should make a greater contribution to Article A (e.g. 1/1) than Article B (e.g. 1/16).

Citation context, which is the contextual information surrounding a citation in the citing articles, can be categorized at the syntactic and semantic levels (Angrosh et al. 2012; Kaplan et al. 2016; Wan and Liu 2014a; Zhang et al. 2013). Syntactic citation context includes citation mention (how many times an article has been mentioned in a citing


A
Are There Better Indices for Evaluation Purposes than the h Index? A Comparison of Nine Different Variants of the h Index Using Data from Biomedicine
B
Interface
The Matthew effect in empirical data
Hirsch, 2005(1 CITATIONS)

Jorge Hirsch (2005) proposed the *h* index as a criterion to quantify the scientific output of a single researcher

From citation distributions [104–109], co-authorship networks [98] and the formation of research teams [110,111], to the ranking of researchers [112–114] and the predictability of their success [72,115–117]—how we do science has become a science in its own right.

Wang D. Song C. Barabási. A.-L. 2013; Seglen. 1992; Redner. 1998; Lehmann S. Lautrup B. Jackson. 2003; Radicchi F. Fortunato S. Castellano C. 2008; Stringer MJ. Sales-Pardo M. Amaral LAN. 2010; Radicchi F. Castellano C. 2012; Guimerà R. Uzzi B. Spiro J. Amaral LAN. 2005; Newman MEJ. 2004; Milojević S. 2014; **Hirsch JE. 2005**; …(16 CITAIONS)

Fig. 1 Different citation contexts of the cited H-article

article) (Ding et al. 2013), as well as citation location (where these references are mentioned in the citing article) (Hu et al. 2013). Semantic citation context includes citation topics, which captures the topic distribution of citation contexts. While these contextual features work well in detecting citation sentiment (Voos and Dagaev 1976), citing behavior (Small 1978), and citing motivation (Moravcsik and Murugesan 1975), they have not been explored in depth to detect impact change of articles over time.

This paper addresses this gap by applying content-based citation analysis to examine the dynamics of the H-article's impact changes as reflected in citation context shifts from 2006 to 2014, where we divide the period into three phases: "Discussion," "Reputation," and "Adoption." Section "Literature review" contains a brief literature review, section "Methodology" discusses data and methodology, section "Results analysis and discussion" describes and discusses results, and section "Conclusion" draws conclusions and points out future research.

Literature review

Macro-level impact decay

The impact decay of articles has been investigated for many decades at the macro level. Burton and Kebler (1960) first used the concept of "half-life" from physics to describe scientific articles' obsolescence function or impact decay, which they defined as "the time during which one-half of all the currently active literature was published" (p. 19). Half-life has been widely adopted by libraries to weed out literature and construct collections (Line and Sandison 1974; Schlachter 1988), or to enhance library services and technical support (Burton and Kebler 1960; Brown 1980; Tsay 1998). For example, Charles (1988) pointed out that the citation count in the Science Citation Index should be normalized to achieve a more interpretable half-life for astronomical papers. Even though the impact decay or obsolescence of scientific publications has been studied, researchers have made limited effort to analyzing the ways in which the impact of an article actually changes over time, e.g., how, where, and how many times one cited article is mentioned in the body of citing articles, which provides information on how the impact of the cited article changes over years.

Citing behavior

There are many reasons for authors' citation practices and trends. Lipetz (1965) identified 29 categories of citation practice motivations, organizing them into four clusters: (1) original scientific contribution or intent of the citing paper, (2) contributions of the citing paper other than its original scientific contribution, (3) identification of relationships between the citing paper and the cited paper, and (4) scientific contribution of the cited paper to the citing paper. Similarly, Moravcsik and Murugesan (1975) divided the citations of physics articles into four categories: conceptual/operational, evolutionary/juxtapositional, organic/perfunctory, and confirmative/negational, where they found that one-third of the references were redundant, one-seventh were negational, and two-fifths were perfunctory. Case and Higgins (2000) used a questionnaire to identify why authors cited highly cited articles, and found that authors do so to promote their own authority, or to claim that the highly cited article deserves attention or criticism.

Citing behavior thus varies considerably in different articles, where some that are heavily cited but are only mentioned sparingly in the citing articles, and others that receive only a moderate number of citations are frequently mentioned by the citing papers (Zhao and Strotmann 2015). Generally, more than one-third of citations occur in the beginning of the citing articles, most of which are perfunctory. Some citations are located in the Method section for operational use and some in the Result and Discussion sections for confirmative use. These diverse locations indicate a range of citation function, and to some extent imply citation impact in the citing articles (Cano 1989). Different citation contexts that contain the same cited article may also discuss different topics. For example, Ruane and Tol (2008) cited the H-article to point out the function of the h-index. Hack et al. (2014) initially mentioned the H-article to discuss the function of the h-index, then to define the h-index, and finally to compare the h-index with other indicators. Some articles only mentioned the H-article (Pathak and Bharati 2014) while others referenced it along with many other articles (Venable et al. 2014).

Content-based citation analysis

Content-based citation analysis (CCA) focuses on the features of citation context (e.g. mention and location) to differentiate scholarly impact (Ding et al. 2014; Small 1978; Teufel 2000). Small (1978) posited that citations are the carriers of specific concepts or topics from the cited articles, which help the concepts interact and influence each other (Liu et al. 2013), pointing that we could misunderstand the contribution of the cited articles to the citing articles without taking citation context into consideration. Voos and Dagaev (1976) found that citation mention and citation location analysis help identify different types of citation contributions, where citation count alone fails to detect such nuances. Similar studies were done by Moravcsik and Murugesan (1975) and Cano (1989), who found that one-third of citations are located at the beginning of the citing articles. Although citation locations suggest different contributions of the cited articles, all these studies rest on small samples or manual data collection, which are hard to generalize.

Advances in natural language processing (NLP) technologies make it possible to semi-automatically investigate the features of citation context in large-scale, full-text articles (Ding et al. 2014; Ding and Stirling 2016). Content-based citation analysis has been further applied in solving various problems related to author co-citation analysis (Jeong et al. 2014; Kim et al. 2016), author ranking (Zhao and Strotmann 2015), and impact evaluation (Ding et al. 2013; McKeown et al. 2016; Wan and Liu 2014b). New researches show that combination of the features of citation context (e.g., citation mention and citation location) has a better potential than merely using citation count to accurately evaluate citation contribution (Ding et al. 2013; Hu et al. 2013; Wan and Liu 2014a). Some scholars have suggested that the citation context topics may not play a major role in an article's impact over time. For example, Small, Tseng, and Patek (2017) recently argued that when the cited articles are highly cited, their citations become standard symbols and the concepts they carry remain unchanged, but they did not provide temporal evidence to support this argument. We agree with scholars who believe that the meaning of citation context in a highly cited article can indeed change over time, and should thus be investigated to identify impact shifts in the citing articles. Even though many studies report a diversity of citation motivations and patterns, little attention has been given to how the impacts of highly cited articles change over time. To fill this gap, we use the citation context of the H-article (Hirsch 2005) to quantitatively analyze specific features of the data collected (Fig. 2) and reveal its impact change in the nine-year period from 2006 to 2014.

Methodology

Data

Cited article data

In this study, we use Hirsch's (2005) paper entitled "An index to quantify an individual's scientific research output" (H-article) as the example of a highly cited and influential article. The h-index has been confirmed in the last decades to be of great importance for evaluating individuals' productivity and impact. Having received a large number of citations in Web of Science (WoS), Hirsch's seminal paper has continued to attract and influence many scholars from diverse domains.

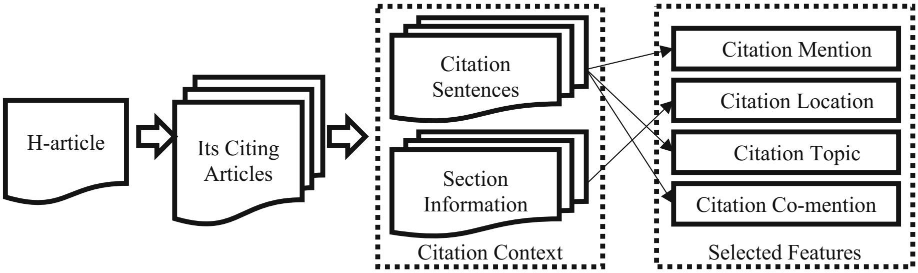


Fig. 2 Overview of data collection and selected features

Full text of citing articles

We collect the full-text articles published between 2006 and 2014 that cite the H-article from the WoS core collection. Articles without full text are omitted. In total, we use 763 full-text citing articles as the data set.

Citation context

In examining citation context, studies usually identify the one sentence that contains the citation as the citation content, and the section where it is located as the citation location (Ding et al. 2013; Hu et al. 2013; Jeong et al. 2014; Tang et al. 2014; Wan and Liu 2014a, b). We thus present the citation contexts of a sample article (Table 1) that mentions the H-article nine times: once in the Introduction, once in the Literature Review, and the rest in the Results and Discussion sections. But if we use article citation count as a criterion to measure the article's impact, where the h-index is only cited by this article once. In total, from 763 articles 1476 citation contexts are collected (Table 2). The total *citation mentions*

Table 1 Citation context sample

ID	Citing article ID	Year	Title	Citation context	
				Citation sentence	Location
1	1	2007	Soil science and the h index	Hirsch (2005) suggested the h (Hirsch) index as a measure of scientific 'output'	Intro.
2				The typical h index depends on the discipline or field of science. The h index of an individual scientist is influenced by: the size or number of scientists in the field, the number of papers produced by the scientists in the field, the average number of citations in the field, and the age of the scientist (Hirsch 2005)	Lit.
3				On the other hand, Hirsch (2005) argues that the larger the field, the larger the number of scientists to share a larger number of citations, so typical h values should not necessarily be larger	R&D
4				Hirsch (2005) suggested the relation between h and the number of total citations c, tot N is given by:	R&D
5				Evidently h is related to the age of the researchers, a relation with age is proposed by Hirsch (2005):	R&D
6				Hirsch (2005) found m 1 characterising a successful scientist, and m 2 for outstanding scientists.	R&D
7				Hirsch (2005) also defined c as the average number of citations per paper per year with the following relationship:	R&D
8				According to Hirsch (2005) realistically c > p, where most contributions to Nc, tot is from the highly cited papers (the h papers that have the number of citations >h)	R&D
9				The maximum h index we found was 51 whereas in biology and physics it is over 100 (HIRSCH 2005)	R&D

Intro. represents Introduction, *Lit.* is Literature Review, and *R&D* is Results and Discussion of each year are found to be greater than the *citing article count* number. For example, in Table 1, the mention of “Hirsch (2005)” occurs nine times, but the citing article count is one, because only one article (Hirsch’s H-article) is listed in the reference part of the sample article. In Table 2, one notes that in 2006 the H-article appears 17 times in the reference parts of the citing articles but is mentioned 32 times in the body of the texts. The table suggests that the ratio of citation sentences to number of citing articles (citing article count) in each year is in a fluctuating decline after a short increase in 2006 and 2007.

Features

A set of features is selected herein to describe the impact change in the citation context, which contains two categories: syntactic features and semantic features.

Syntactic features

The syntactic features include an article’s citing article count, citation mention, and citation location. For each citing article, the citing article count always equals one, because the H-article can only be noted once in the single reference list of a citing article. *Citation mention* is the number of times that the H-article is mentioned (e.g., “Hirsch (2005) suggested the h (Hirsch) index as a measure of scientific ‘output’” (Minasny et al. 2007, p. 258). within the full text of the citing article (Ding et al. 2013; Wan and Liu 2014a). *Citation location* is where a cited paper in the citing article is noted (Hu et al. 2013), such as the Introduction (Intro.), Literature Review (Lit.), Methodology (Meth.), Results and Discussion (R&D), or Conclusions (Con.). We use the section information to calculate the citation location distribution and the number of distinct locations in citing articles published in each year between 2006 and 2014. For example, in Table 1, the distribution of citation location in the sample article is shown as 11 percent (Intro.), 11 percent (Lit.), and 78 percent (R&D), making three distinct citation locations.

Table 2 Numbers of citing papers collected each year

Year	# of citing articles	# of citation sentences	Ratio of citation sentences
2006	17	32	1.88
2007	23	70	3.04
2008	60	141	2.35
2009	88	148	1.68
2010	97	211	2.18
2011	109	208	1.91
2012	125	211	1.69
2013	133	261	1.96
2014	111	194	1.75

Semantic features

The semantic features include citation co-mention and citation topic. *Citation co-mention* means the number of other citations besides the H-article that are co-mentioned in the same citation sentence of the H-article (Wan and Liu 2014a). For example, in the first sentence of the sample article that mentions the H-article in Table 1 ("Hirsch (2005) suggested the h (Hirsch) index as a measure of scientific 'output'" (Minasny et al. 2007, p. 258).), the citation co-mention is one because only the H-article is mentioned there. The average citation co-mention of the sample article is also one (9/9 = 1). *Citation topic* is the topic distribution of the citation sentences extracted from the citing articles (Liu et al. 2013). This study uses citation content to extract topics (shown in Fig. 2). We adopt these two co-mention and topic citation categories to analyze the H-article's impact change over time.

Data analysis

For data analysis, we select several indicators to measure citing article count, citation mention, citation location, citation topic, and citation co-mention. The indicators and their features are shown in Table 3. Table 4 shows one example and explains how we calculate these indicators.

(1) Average citing article count:

$$\text{Average citing article count} = \frac{\sum_{i=1}^{n} \text{Citing article count}_i}{N} \tag{1}$$

In Table 4, the average citing article count in 2006 $= \frac{1+1+1+1+1}{5} = 1$

(2) Average citation mention:

$$\text{Average citation mention} = \frac{\sum_{i=1}^{n} \text{Citation mention}_i}{N} \tag{2}$$

In Table 4, the Average Citation Mention in 2006 $= \frac{2+3+4+2+1}{5} = 1.2$

(3) Average number of distinct citation location (ADCL):

Table 3 Indicators

Indicator	Features
Average citing article count	Citing article count
Average citation mention	Citation mention
Citation location distribution	Citation location
Average number of distinct citation location	Citation location
Top 30 keywords of citation sentences	Citation topic
Topic similarity based on topics in fixed year	Citation topic
Topic similarity between every two continuous years	Citation topic
Average citation co-mention	Citation co-mention

Table 4 Data sample in 2006

Article ID	Citing article count	Citation mention	Number of distinct locations	Average citation co-mention
1	1	2	2	1.5
2	1	3	2	2
3	1	4	3	2.5
4	1	2	1	1
5	1	1	1	3

$$\mathrm{ADCL} = \frac{\sum_{i=1}^{n} \text{Number of distinct location}_i}{N} \tag{3}$$

In Table 4, the ADCL in 2006 $= \frac{2+2+3+1+1}{5} = 1.8$

(4) Average citation co-mention:

$$\text{Average citation co-mention} = \frac{\sum_{i=1}^{n} \text{Average citation co}-\text{mention}_i}{N} \tag{4}$$

In Table 4, the average citation co-mention in 2006 $= \frac{1.5+2+2.5+1+3}{5} = 2$

(5) Citation location distribution:

Table 5 shows the section information of all the citation mentions of the H-article, so that we can examine the location distributions of these mentions over time.

(6) Top 30 keywords of citation sentences:

Topic extraction. Three main methods and algorithms are available to extract document topics: TFIDF (Salton and Buckley 1988), LDA (Blei et al. 2003), and LSA (Dumais 2004). The first two are most frequently used (Alsaad and Abbod 2015; Hu et al. 2015; Lee et al. 2015). Both LDA and TFIDF are applied to extract topics in this research, but we finally use the results from TFIDF because it generates better interpretable results than LDA. The top 30 words ranked by TFIDF values are therefore used to represent the topics in each year. General, special, and high-frequency words are removed (e.g. the h-index). Formula (5) for computing the TFIDF values of words is as follows:

Table 5 Location distribution of citation mentions from 2006 to 2014

Year	Intro.	Lit.	Meth.	R&D	Con.
2006	15*	1	4	3	5
2007	25	3	8	13	7
2008	77	16	21	4	7
2009	77	22	18	6	2
2010	84	19	59	12	6
2011	92	17	41	19	3
2012	81	21	49	26	5
2013	114	26	49	29	12
2014	73	13	59	24	6

* The number 15 in 2006 means this year 15 sentences in total mention the H-article in the Introduction

$$\mathrm{TFIDF_w} = \mathrm{Tf_w} \times \log_2\left(\frac{\mathrm{Doc}}{\mathrm{Df_w}}\right) \tag{5}$$

$\mathrm{Tf_w}$ is the frequency that the word w appears in a set of keywords; Doc represents the number of documents in the whole document set; and Df_w denotes the number of documents that contain the word w.

Topic similarity. Jaccard coefficient is used to track changes of topic similarity at the topic level between 2 years (Formula (6)):

$$\mathrm{Jaccard}(X, Y) = \frac{|X \cap Y|}{|X \cup Y|} \times 100\%, (X \cup Y \neq \emptyset) \tag{6}$$

Here, X and Y represent a topic set extracted by TFIDF in different years, respectively. $|X \cap Y|$ represents the number of the keywords the two sets share; $|X \cup Y|$ shows the amount of all the distinct elements the two sets contain.

(1) Topic Similarity Based on Topics in the Fixed Year:
The year 2006 is selected as the fixed year and Formula (6) is used to compute the topic similarity from 2007 to 2014 with 2006 to detect topic differences, such as similarity between 2006 and 2007, and similarity between 2006 and 2008. This approach helps us locate the topic shift from the initial citation context in 2006, 1 year after the H-article was published.

(2) Topic Similarity between Every Two Continuous Years:
Topic similarity between every two continuous years is calculated using Formula (6) as well, such as topic similarity between 2006 and 2007, and topic similarity between 2007 and 2008. This similarity component compares the topics of the citation contexts between two continuous years to identify topic shifts from the previous year.

Results analysis and discussion

Citing article count and citation mentions

We plot the average citing article counts and average citation mentions in Fig. 3. The average citing article counts equal one from 2006 to 2014. By contrast, the average citation mentions change in counts every year and peak at three in 2007 before fluctuating to below 1.7 in 2009 and 2012. That indicates that the citing papers all mention the H-article more than once (similar to the findings in recent researches, e.g. Ding et al. 2013; Hu et al. 2013) and less frequently after 2007.

Citation location

Figure 4 presents the location distribution of citation mentions. Generally, more than 40 percent of citation mentions appear in the Introduction of the citing articles every year, with small fluctuations. We take citation mentions in 2008 as an example to show usage of H-article in citation context. We find that 43 out of 60 citing articles mention the H-article in the Introduction 77 times, 1.8 times per article on average.

Out of the 77 mentions, 22 simply note that the H-article is popular, e.g. "Since Hirsch's first publication of the h-index in 2005 [9], this new measurement of academic impact has

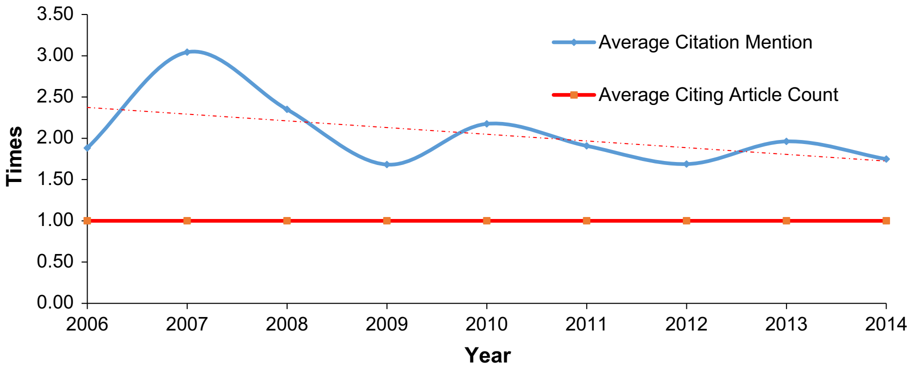


Fig. 3 Citing article counts and citation mentions 2006–2014

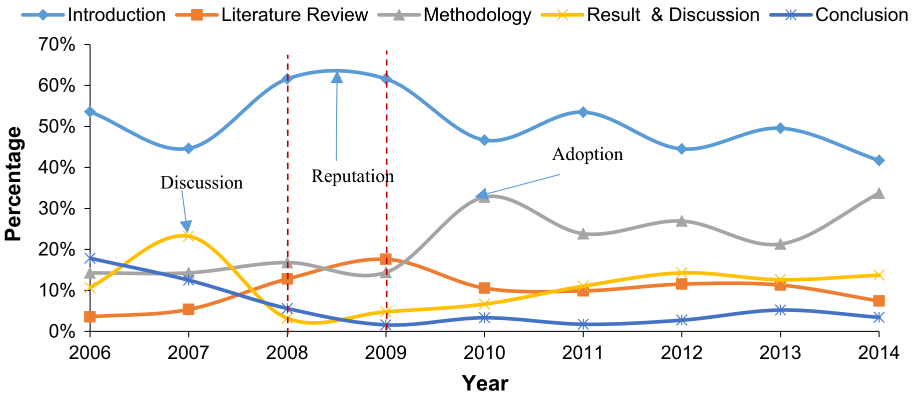


Fig. 4 Location distribution of H-article citation mentions 2006–2014

generated widespread interest" (Baneyx 2008, p. 364). A total of 45 of the 77 mentions introduce the definition or function of h-index, e.g. "A simple and popular one among the possibilities is the h-index, the Hirsch index (Hirsch 2005), which is an indicator for lifetime achievement of a scholar" (Järvelin and Persson 2008, p. 1433); "I have recently [16] shown that self-citations significantly reduce the h index in contrast to Hirsch's expectations [1]" (Schreiber 2008, p. 188). Ten note specific applications of the h-index, e.g. "In this paper we tried to provide a partial answer by considering the h-indexes [Hirsch 2005A, B] of a group of highly cited researchers based on each of the three citation databases" (Bar-Ilan 2008, p. 258).

From these instances we can see that mentions of the H-article in the Introduction are at times perfunctory. The major reason is to provide the definition of the h-index and its function.

Citation mentions located in other parts of the citing article change more frequently than those in the Introduction. For instance, in the R&D, citation mention peaks in 2007. Nine out of 23 citing papers mention H-article 28 times, which is three times per citing article on average. Among these mentions, 17 discuss the pros and cons of the h-index, such the article of (Pulina and Ana Helena Dias 2007): "Hirsch (2005) states that even though Ci.

properly measures the total impact of a scientist's activity, it has the following disadvantages: (1) it is hard to find, (2) it may be inflated by few big hits, which may not be representative of the individual if he/she is coauthor with many others on those papers and will correspond to a very atypical value of the a parameter (a = Ci./h2), larger than 5, and (3) it gives undue weight to highly cited review articles versus original research contributions" (p. 97). Six mention the H-article to present results, e.g. "The effect of the citing population size was exemplified by Hirsch (2005) by comparing Physics and Biology, the latter reaching much higher h values" (Imperial and Rodríguez-Navarro 2007, p. 274). After 2007, citation mentions appear less in the R&D.

In the Methodology, citation mention reaches its largest portion in 2010 over the years, when 38 out of 97 citing articles mention the H-article 59 times (1.6 times on average). In these 59 mentions, 18 introduce the h-index by defining it, e.g. "The h index is defined as follows (Hirsch 2005): A scientist has index h if h of his or her Np papers have at least h citations each and the other (Np−h) papers have h citations each" (Lazaridis 2010, p. 212); 17 describe the function or features of h-index, e.g. "The h-index has recently got attention and is assumed to be a robust measure for scientific performance and impact (Hirsch 2005)" (Mikki 2010, p. 322); "Due to its simplicity and meaningfulness, Hirsch's h index (Hirsch 2005) has created quite a stir in the scientific community" (Lazaridis 2010, p. 212). Other mentions include comparing the h-index with its variants [e.g. g-index (Egghe 2006) and h(2) index (Kosmulski 2006)]. After 2010, citation mention makes up a stable and relative high portion in the Methodology. On the contrary, citation mention shows quite low frequencies in the Literature Review and the Conclusion.

In-depth analysis of citation mentions and the corresponding locations allows us to divide the period (2006–2014) into three phases: "Discussion," "Reputation," and "Adoption" (Table 6). In the Discussion phase, many citation mentions of the H-article are distributed in the Introduction and R&D. The H-article is widely and heavily discussed in the R&D (nine of 29 articles and three times per article). Moreover, a range of variants like the g-index (Egghe 2006) and the h(2) index (Kosmulski 2006) have been proposed in this

Table 6 Descriptions of the three phases of citation data collected

Phase	Definition	Features	Regarding H-article	Period
Discussion	In this phase, many citing articles discuss the function and features of h-index and propose its variants by citing the H-article	Many citing articles cite and mention the H-article in R&D several times	Most of the mentions discuss the function and pros/cons of the h-index	2006–2008
Reputation	In this phase, most mentions of the H-article are in the Introductions with only a few in other parts	Most mentions are perfunctory	Many citing articles cite the definition of the h-index and mention its fame using shorter sentences	2008–2009
Adoption	Mentions appear in the Introduction and Methodology part	The h-index is either introduced as a method or compared with other methods	Articles cite the definition, state the features of the h-index, and compare them with similar indexes	2009–2014

phase. In the Reputation phase, citation mentions are largely distributed in the Introduction for reasons related to the fame of the H-article or the definition of the h-index. In the Adoption phase, most of the mentions appear in the Introduction and Methodology sections, where citing articles generally compare the h-index with other indicators or adopt it in their studies.

These three phases indicate that the H-article has been mentioned for different purposes over time, from its optimization and comparison with other methods to its application. Figure 5 plots the distinct citation locations of the H-article over the 9-year period of data collection, showing that the diversity of citation location peaks in 2007 and declines thereafter with fluctuations. After combining these data with results in Fig. 4, we find that mentions of the H-article are located in various sections (e.g. R&D and Methodology). After 2007, however, the mentions mainly appear only in Methodology and Introduction sections.

Citation co-mention

Another way to observe the impact change of the article is to analyze how it is co-mentioned with other articles within the same citation contents. Figure 6 illustrates the average citation co-mention and its standard deviation over time. The blue curve indicates a marginal increase in mentions from 1.7 in 2006 to 2.4 in 2014, meaning that more articles are co-mentioned with the H-article during this period.

Citation topic similarity

TFIDF value for each word in citation content per year is calculated. The top 30 words with the highest TFIDF values are selected as the topical words in each year (Table 7). Words put in bold indicate that they are either independent from the h-index definition or are newly extracted in that year. The majority of topical words refer to the definition of the h-index, e.g. "measure," "individual," and "output." They are usually found in sentences such as, "The h index for a scientist is the number of papers that the scientist has authored that have received ≥ h citations (8)" (Ioannidis 2010, p. 4636). This is reasonable since all the citation sentences mention the h-index to some degree, although the rest of these words also reveal some changes.

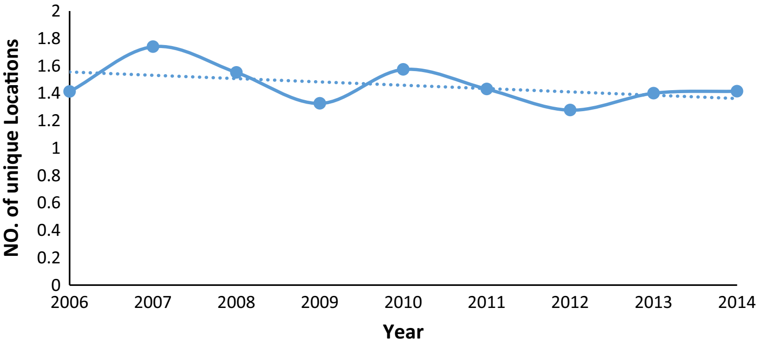


Fig. 5 Average Citation Location Diversity of H-article mentions in each year

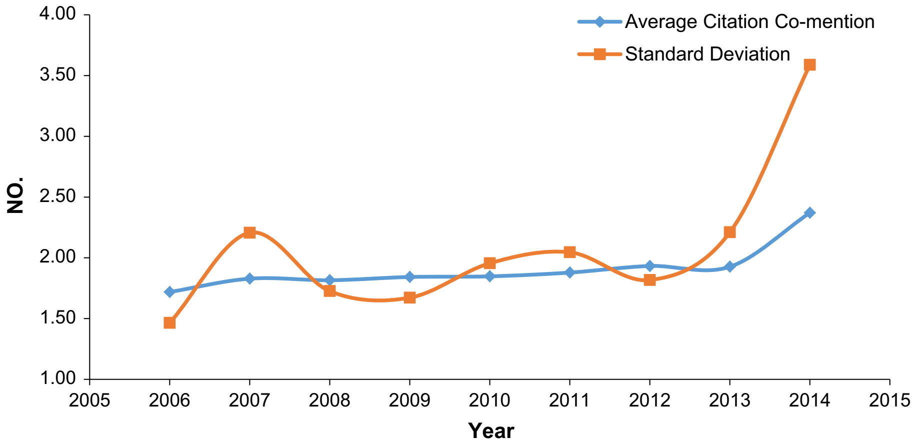


Fig. 6 Average number of citation co-mentions in citation sentences and standard deviations 2006–2014

Table 7 Yearly distribution of top 30 words with high TEIDF values

Year	Top 30 words
2006	output; measure; individual; work; quantify; ranking; physicist; given; simple; performance; high; article; shown; cumulative; use; **braun**; result; case; physic; particular; papers; **ball**; significant; researcher; order; science; model; assessment; age; arbitrary;
2007	individual; researcher; measure; output; value; field; year; science; age; physic; physicist; article; time; average; quantify; **ball**; **database**; parameter; higher; low; mentioned; productivity; relation; single; metric; identify; **advantage**; larger; career; **2006**;
2008	researcher; measure; follows; author; output; year; fewer; physicist; individual; **2007**; **2006**; bibliometric; article; time; simple; value; quality; **popular**; single; equal; original; increase; quantify; definition; count; **novel**; ranking; contribution; academic; field;
2009	**2006**; individual; output; researcher; **2007**; quantify; measure; author; article; performance; productivity; time; original; follows; rank; **egghe**; year; **glänzel**; highest; factor; simple; study; model; quality; **braun**; developed; level; way; scholar; **raan**;
2010	individual; measure; researcher; output; author; **2007**; **2006**; definition; quantify; article; value; group; **2008**; factor; science; study; original; time; simple; performance; year; **egghe**; metric; **popular**; general; quantity; originally; career; single; **quotient**;
2011	researcher; measure; individual; author; article; quality; productivity; output; **2006**; **field**; single; work; factor; academic; bibliometric; time; **2007**; cumulative; widely; rank; **community**; production; **egghe**; metric; year; ass; physicist; **2010**; follows; tool;
2012	measure; individual; output; author; researcher; **2010**; productivity; article; time; performance; **2006**; quantify; scholar; metric; **egghe**; **2009**; bibliometric; year; quality; **alonso**; originally; example; **2008**; evaluating; work; average; evaluate; developed; designed; original;
2013	measure; researcher; individual; author; productivity; time; output; **2006**; article; **egghe**; academic; year; quantify; quality; single; **2007**; use; factor; quantity; bibliometric; value; metric; work; contribution; **widely**; attention; **burrell**; **2009**; count; significance;
2014	measure; author; productivity; researcher; individual; article; **2010**; performance; time; **2006**; count; account; metric; bibliometric; year; developed; example; factor; work; achievement; quotient; academic; useful; **popular**; output; known; information; quality; cumulative; **egghe**;

In the Discussion phase, most of studies still focus on examining and optimizing the h-index, yet also invent new indicators, using words such as, "advantage," "parameter," "braun," and "ball" (marked in bold). After Egghe proposed the g-index (Egghe 2006) and Kosmulski proposed the h(2) index (Kosmulski 2006) in 2006, their articles are frequently co-mentioned with the H-article thereafter. Many publications also discuss the function and potential future of the h-index in 2006 and 2007 (e.g. Ball 2005; Bornmann and Daniel 2007; Braun et al. 2006; Hirsch 2007; Oppenheim 2007).

In the Reputation phase, the H-article as well as its fellow studies gain fame in Bibliometrics, since many citing articles mention keywords such as "popular," and "novel" that attract attention. These words have been frequently co-mentioned with other articles in the Introduction of citing articles, for example, "2007," "2006," "egghe," and "glänzel."

In the Adoption phase, more and more articles are co-mentioned with the H-article since more words related to years pop up (e.g. "2009" and "2010"). Meanwhile, some other keywords indicate that the H-index has been applied to evaluating the scientific performance of groups or organizations not just to the evaluation of individual performance, e.g. "group," "community," and "field." The H-article is thus mentioned in the Methodology along with other analytical methods (e.g. social network analysis). As seen in Table 8, the h-index has been combined with other indicators or methods as indicated in the citation content.

The Jaccard coefficient is applied to calculate the similarity between the yearly topics in two ways (Fig. 7): to compare keywords in each year with the keywords used in 2006 (Similarity A), and to compare keywords between every two continuous years (Similarity B).

Similarity A shows a gradual decrease with slight fluctuations after 2009. The decline shows that the citation topics change only slightly over the years. In the first two phases (2007–2008) where the H-article is usually the sole article mentioned in citation content, the topics change marginally. By contrast, from 2009 on, when the H-article enters the Adoption phase, the similarity of keywords keeps decreasing, since the newly emerged topics, such as "organizational evaluation" in applied studies (which are usually conducted in differentiated fields) can easily diverge from initial topic's focus over time. Similarity B after 2009 shows a sharp increase every two or three years (from 2007 to 2010, and from 2010 to 2013 where it peaks), and is usually larger than Similarity A. This indicates that the citation topics between continuous years are somewhat similar (Similarity B), yet vary

Table 8 Citation content examples

Author/s	Year	Citation Content/Title
Schuetz, Philipp and Caflisch, Amedeo Cobo,	2008	To cover linguistic applications we benchmark the word association network … and the graph of the coappearing words in publication titles (co) authored by Martin Karplus … who has the third highest h factor … among chemists …
M. J. et al.	2012	As described in …, the performance analysis uses bibliometric measures and indicators (based on citations), such as the h-index (…), g-index (…), hg-index (…), or q2-index (…) to quantify the importance, impact, and quality of the different elements of the maps (e.g., clusters), and also of the network

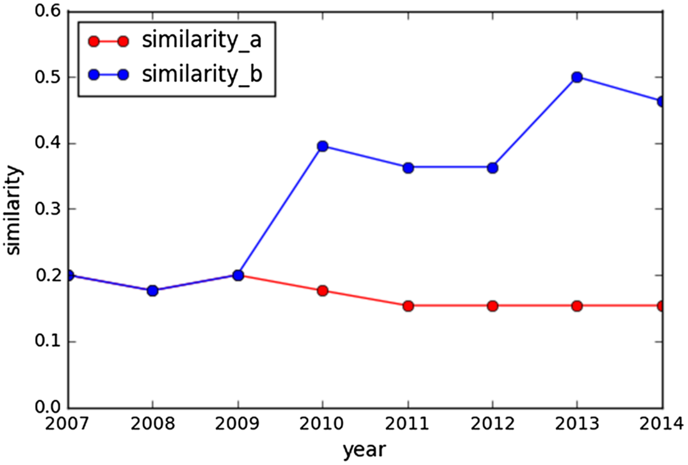


Fig. 7 Topic similarity in two different ways based on years

more broadly in terms of keywords usage, which shows stronger shifts (Similarity A). In the first two phases of Discussion and Reputation (2006–2009), the two types of similarity show similar trends before splitting. This data show evidence of a larger degree of topic drift in the Adoption phase when the H-article is mentioned for specific applications.

Conclusion

In our use of citation context and its features of citation mention, citation location, and citation topic to track how the impact of a Hirsch's highly cited article (2005) changes over time, this study contrasts standard citation research that posits the average citing article count as always one, thus discounting the impact of citation mentions over time. The use of average citation mentions shows different trends over time, however, as shown in study results collected over the nine-year period from 2006 to 2014. In the first two years, mentions of the H-article increase to peak in 2007 and continue to fall with fluctuation until 2014. The distribution of citation location also indicates different phases, where the citing behavior of the H-article changes from general examination ("Discussion"), its status in the field ("Reputation"), and application by citers ("Adoption"). The average number of the H-articles' co-mentioned articles keeps growing, indicating more and more cited articles in the citing articles are noted in the same sentences and share contributions with H-article. The top 30 keywords of citation contents in each year reveal an impact change of the H-article, from mainly citing the definition and function of the h-index to gradually adopting or applying it to other domains. This research therefore demonstrates the dynamic changes of patterns in article citation mentions, and argues that only using citation counts to measure the H-article's impact changes does not offer a broad measure of its influence over time.

The limitation of this study is that it only selects one highly cited article to highlight impact changes over a period of nine years. More large-scale investigations should be conducted in the future to better understand how and why these impacts change, using other articles of impact. These investigations can help us facilitate the evaluation of highly cited articles and their influence in a more nuanced manner, and promote better scholarly communication and understanding of scholarly obsolescence over time. This is a hugely important topic in light of ongoing advances in scientific knowledge and technology, where scholars' status, their funding, and the readers of science are deeply affected by new knowledge that replaces their own.

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