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Brahim Hamadicharef

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# BRAIN-COMPUTER INTERFACE (BCI) LITERATURE - A BIBLIOMETRIC STUDY

*Brahim Hamadicharef*

Tiara #22-02  
1 Kim Seng Walk  
Singapore 239403

## ABSTRACT

Brain-Computer Interface (BCI) is a relatively young research field which has seen a growing interest with associated number of publications over the last two decades. In this study we present the first bibliometric analysis of the BCI literature (1990–2008) from the Thomson Reuters's Institute for Scientific Information (ISI) Web of Knowledge. Thus, the main objectives of this bibliometric study are: 1) to explore the growth of BCI literature, 2) to assess if it follows Lotka's law of scientific productivity, 3) to identify authors, groups and countries contributing the most to BCI, 4) to reveal the characteristic of citation for the BCI literature, and finally, 5) to determine the core journals that published substantial portions of the literature on BCI. Results indicate that BCI literature follows a power law growth, has an average author count of 3.9 and an average page count of 7.09. More than half (52.73%) of the BCI literature is never cited, and 14 papers have been cited more than 100 times. The 3 most productive authors are leading BCI research groups, in Austria, Germany and the USA.

## 1. INTRODUCTION

Brain-Computer Interface (BCI) is a relatively recent research field which has witnessed a growing number of publications over the last two decades. Still to provide a clear view of the current state-of-the-art and who are the eminent authors in the field, there is yet no such scientometric or bibliometric study.

In a nutshell, BCI, also named Brain-Machine Interface (BMI) when using invasive EEG [5], allows by means of Electroencephalogram (EEG) to communicate (for e.g. word spelling) and control external devices, for example a wheelchair. Recently it has found new applications in stroke rehabilitation, as new paradigm for assistive medical devices, helping to improve people's quality of life in their daily activities, and even gaming [18].

After nearly two decades of research and development in BCI, a bibliometric analysis is timely to study the field. Thus, the main objectives of this bibliometric study are: 1) to explore the growth of BCI literature, 2) to assess if it follows Lotka's law of scientific productivity, 3) to identify authors, groups and countries contributing the most to BCI, 4) to reveal its citation characteristic, and finally, 5) to determine the core journals that published substantial

portions of the literature on BCI.

The remainder of this paper is organized as follows. In Section 2, the bibliometric analysis methodology is presented. In Section 3, we present results based on a large BCI citation database from 1990 to 2008. Finally, in Section 4, we conclude the paper.

## 2. METHODOLOGY

We created a database of the BCI literature using Thomson Reuters's Institute for Scientific Information (ISI) Web of Knowledge<sup>1</sup>. The search, using the topic term 'Brain-Computer Interface', was limited to the period from 1990 to 2008. Yearly record provides the publication title, authors' names, journal details, page count, number of times the publication was cited, etc. In total, 1081 publications were retrieved for this bibliometric study.

## 3. RESULTS

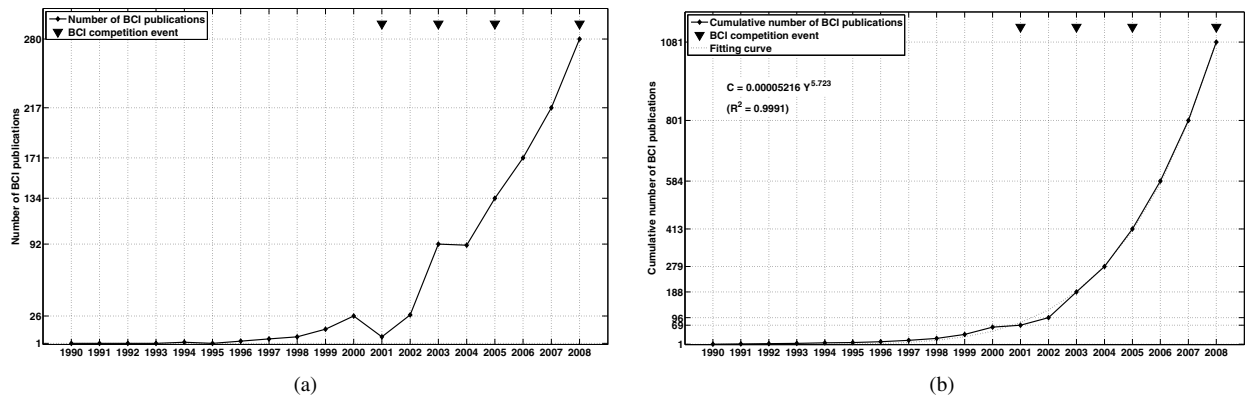
### 3.1. Growth of BCI Literature

Figure 1(a) shows the BCI publications count evolution on a yearly basis. Not shown in the ISI records, the earliest paper describing a BCI system was published in 1973 by J. J. Vidal [12]. Two decades later, pioneer BCI research by J. Wolpaw was first published in 1990 [15] and 1991 [17], followed by small numbers of papers in the 90's. This grew substantially since 2003, augmenting to 92 in 2003, to 171 in 2006, to 217 in 2007, and 280 in 2008. One could speculate that the BCI competitions (first organized in 2001, then 2003, 2005 and more recently in 2008) have helped to sustain such rate of growth.

Of the 1081 publications, 586 were published in 178 journals and 495 were published in conference proceedings. On average, 57 publications have been published each year by 230 authors. The average is 3.9 authors per paper, page count of 7.06, and papers are cited on average 38.43 times (per year). Clearly after 2001, publications counts has steadily increased every year. We plot the cumulative count of BCI literature in Figure 1(b). The cumulative count follows a power law model, defined as:

$$C = \beta Y^\alpha \quad (1)$$

<sup>1</sup>www.isiknowledge.com



**Fig. 1.** BCI literature: a) Growth and b) Cumulative count

where  $C$  is the cumulative number of BCI publications and  $Y$  is the number of years since 1990. Using the curve fitting tool from MATLAB to estimate  $\beta$  and  $\alpha$ , we obtained  $\beta = 0.00005216$  and  $\alpha = 5.723$ , with a goodness-of-fit  $R^2 = 0.9991$ .

### 3.2. Authorship Pattern

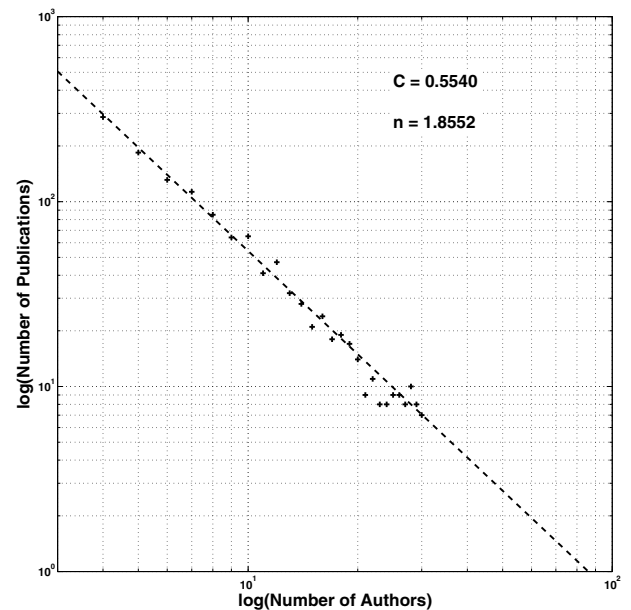
From the 4355 authors who wrote the 1081 publications, 1808 are unique authors. About 1120 (25.71%) authors have only one publication and 293 (6.72%) authors have two publications. Lotka's law [6], an inverse square law, was used to find authors productivity patterns. It typically states that for every 100 authors contributing to one article, 25 will contribute 2, 11 will contribute 3, etc. (i.e.  $1/n^2$ ). According to Lotka's law of scientific productivity, only 6% of the authors in the field will produce more than 10 articles. The general form of Lotka's law is defined as:

$$y = C/x^n \quad (2)$$

where  $x$  is the number of contributing authors and  $y$  is the number of publications. The exponent  $n$  and constant  $C$  are estimated, respectively, by linear least square fitting and an approximation function [9]. We find  $n = 1.8552$  and  $C = 0.5540$ . Figure 2 shows the Log-Log plot of the number of author and their corresponding number of publications. Using the Kolmogorov-Smirnov test (KS-test) of goodness-of-fit we find that the null hypothesis that the BCI literature conforms to Lotka law must be rejected at 0.01 level of significance.

### 3.3. Most Productive BCI Authors

The list of the 30 most productive BCI authors, with in '()' their number of publications referred in the ISI database, is as follows: Gert Pfurtscheller (95), Niels Birbaumer (63), Jonathan Wolpaw (55), Dennis McFarland (43), Gerwin Schalk (36), Xiaorong Gao (34), Gary Birch (33), Christa Neuper (28), Benjamin Blankertz (29), Shangkai Gao (29), Andrea Kubler (28), Cuntai Guan (26), Reinhold Scherer (26), Thilo Hinterberger (25), Klaus-Robert Müller (25), Gabriel Curio (23), Theresa Vaughan (23), Maria Marciani (22), Febo Cincotti (18), Fabio Babiloni



**Fig. 2.** Log-Log plot of the number of author and the number of publications

(17), Christoph Guger (17), Steven Mason, (17), Alois Schlögl (17), Luigi Bianchi (16), Guido Dornhege (16), Bin He (16), Bo Hong (16), Dean Krusienski (16), Rabab Ward (16), Haihong Zhang (19).

G. Pfurtscheller, N. Birbaumer and J. Wolpaw are clearly the most productive authors in BCI research, each leading BCI research group, respectively, at Graz University of Technology (Austria), the University of Tübingen (Germany), and the Wadsworth Center (New York, USA).

### 3.4. Citation pattern

The citation pattern distribution of the BCI literature is shown in Figure 3. It shows that more than half (52.73%) of BCI publications is never cited, 12.77% cited between 3 and 10 times, 15.17% cited between 11 and 50 times, and that top BCI articles (1.3%) are cited more than 100 times. Cited 623, 262, 222, 195, 185, 182, 174, 163, 130, 104, 103, 101 and 101 times, respectively, the top cited

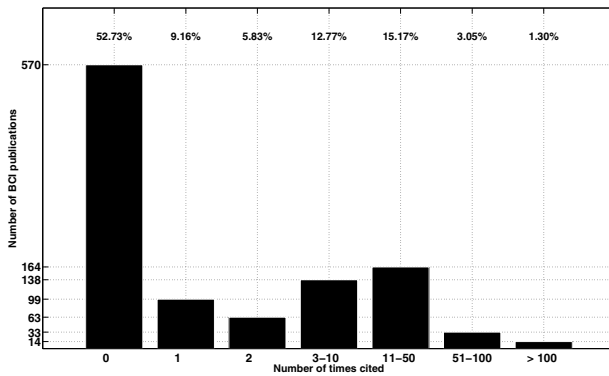


Fig. 3. Citation pattern of BCI literature

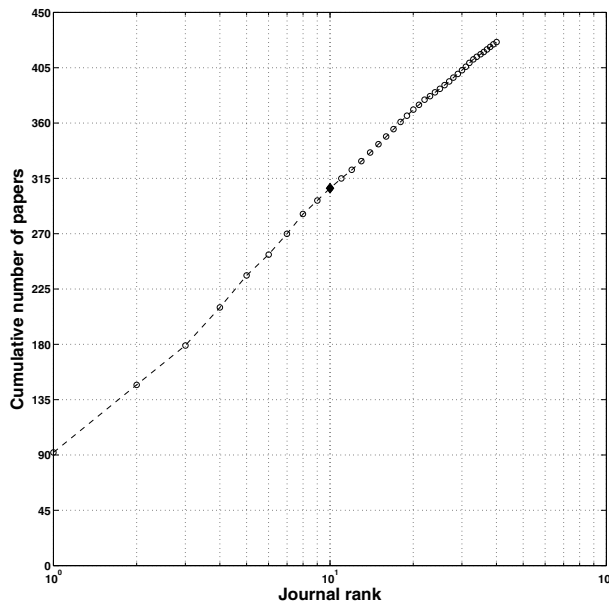


Fig. 4. Bradford curve showing journal rank (log scale) versus number of publications

BCI papers are the following: [18],[3],[13],[17],[2],[19],[14],[4],[10],[8],[16],[1],[11].

### 3.5. BCI Core Journals

The Bradford's law was used to find the BCI core journals using the 586 articles published in 178 journals. The Bradford curve, as shown in Figure 4, shows the journal rank (log scale) versus its number of publications, showing that there are 10 core journals (as listed in Table 1). IEEE Transactions on Neural Systems and Rehabilitation Engineering published 92 articles (8.51% of the total BCI literature), followed by IEEE Transactions on Biomedical Engineering with 55 articles (5.09%). The top 10 BCI core journals account for 28.41% of the total BCI literature, with impact factor varying from 0.888 (Biomedizinische Technik) to 5.694 (NeuroImage) and a mean of 2.5215. Notice that journal Transactions on Neural Systems and Rehabilitation Engineering (#1) is the continuation of Transactions on Rehabilitation Engineering (1993–2000)(#6) journal.

## 4. CONCLUSION

In this paper we presented the first bibliometric study of the BCI literature. Using the ISI Web of Knowledge, we searched publication records from 1990 to 2008. The study revealed the following. A total of 1081 publications were retrieved with 495 published in conference proceedings and 586 published in 178 journals, with an average of 3.9 authors per paper. The cumulative publication count follows a power law model, with significant growth since 2001. Surprisingly 52.73% of the BCI literature is never cited, 14 key articles have been cited more than 100 times. We find that the BCI literature does not follow Lotka's law (verified by KS-test). G. Pfurtscheller, N. Birbaumer and J. Wolpaw are the most productive authors. The top two journals to publish BCI research are the IEEE Transactions on Neural Systems and Rehabilitation Engineering and IEEE Transactions on Biomedical Engineering.

The list of most productive authors will serve as the basis for an Author Co-citation Analysis (ACA) [7] to study author's relationship within the BCI research space.

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**Table 1.** Core journals publishing BCI literature

Rank	Name of the journal	NP	%	IF	PF	Publisher
#1	IEEE Transactions on Neural Systems and Rehabilitation Engineering	92	8.51	2.700	4	IEEE
#2	IEEE Transactions on Biomedical Engineering	55	5.09	1.398	12	IEEE
#3	Clinical NeuroPhysiology	32	2.96	2.972	12	Elsevier
#4	Journal of Neural Engineering	31	2.87	2.737	4	IOP
#5	Journal of NeuroScience Methods	26	2.41	2.092	18	Elsevier
#6	IEEE Transactions on Rehabilitation Engineering	17	1.57	2.036	4	IEEE
#7	Medical & Biological Engineering & Computing	17	1.57	1.379	12	Springer
#8	PsychoPhysiology	16	1.48	3.318	6	Wiley
#9	Biomedizinische Technik	11	1.02	0.889	6	Walter de Gruyter
#10	NeuroImage	10	0.93	5.694	20	Elsevier

NP: number of publications, IF: impact factor, PF: publication frequency (issues/year)

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