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Research article

Scientific profile of brain–computer interfaces: Bibliometric analysis in a 10-year period

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HIGHLIGHTS

- Brain–computer interface (BCI)/Brain–machine interface (BMI) research and the relevant literature have expanded.
- Analysis of highly cited articles can help identify outstanding scientific studies.
- We investigated 100 highly cited BCI papers in the past 10 years, which can help distinguish between incremental and transformational studies.
- It provides insights into priorities and trends for guiding future BCI studies.

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ABSTRACT

Background: With the tremendous advances in the field of brain–computer interfaces (BCI), the literature in this field has grown exponentially; examination of highly cited articles is a tool that can help identify outstanding scientific studies and landmark papers. This study examined the characteristics of 100 highly cited BCI papers over the past 10 years.

Methods: The Web of Science was searched for highly cited papers related to BCI research published from 2006 to 2015. The top 100 highly cited articles were identified. The number of citations and countries, and the corresponding institutions, year of publication, study design, and research area were noted and analyzed.

Results: The 100 highly cited articles had a mean of 137.1(SE: 15.38) citations. These articles were published in 45 high-impact journals, and mostly in *TRANSACTIONS ON BIOMEDICAL ENGINEERING* ($n = 14$). Of the 100 articles, 72 were original articles and the rest were review articles. These articles came from 15 countries, with the USA contributing most of the highly cited articles ($n = 52$). Fifty-seven institutions produced these 100 highly cited articles, led by Duke University ($n = 7$).

Conclusions: This study provides a historical perspective on the progress in the field of BCI, allows recognition of the most influential reports, and provides useful information that can indicate areas requiring further investigation.

1. Introduction

Brain–computer interfaces (BCI), also called brain–machine interfaces (BMI), can create a direct communication pathway between the brain and an external device. Research on BCI began in the 1970s [1]; following years of animal experimentation, the first report of a BCI device implanted in a human appeared in 1998 [2].

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In the last few decades, BCI has emerged as a rapidly developing research area, and studies have focused on researching, mapping, assisting, augmenting, or repairing human cognitive or sensory-motor functions [3]. BCI research usually involves collaboration of multidisciplinary teams of researchers, including those from the fields of neuroscience, orthopedics, rehabilitation, computer science, and engineering [4]. Thus, the BCI literature encompasses reports from numerous researchers varying in specialties and countries of origin, and appearing in a range of scientific journals.

With the development of internet-based search engines, many methods for searching for relevant medical literature are now available. However, the results of basic keyword or topic searches are often overwhelming and shed little light on the most relevant articles. The Institute for Scientific Information (ISI) initiated Science Citations as a systematic approach for evaluating the impact of scientific journals or researchers according to the number of times their works have been cited by other authors [5], and it is widely used to measure the impact of certain papers, helping researchers to find important articles in their area of interest rapidly. This type of analysis has been applied to literature on different specialties and research areas [6–11], and there were earlier bibliometric analyses of the BCI literature, included years from 1990 to 2009[12,13], However, since this is a rapidly growing research area, little is currently known about the most frequently cited articles that are specifically related to BCI research in the latest decade.

Therefore, the purpose of this study was to identify the 100 most highly cited articles in the BCI field in the past 10 years, in an effort to evaluate important contributions to the literature in this promising area.

2. Materials and methods

Thomson Reuter's Web of Science was queried through the Harvard Library Portal, on one specific day, January 1, 2016, to avoid any changes in citation rate as far as possible, for all articles related to BCI published from 2006 to 2015. Different combination of the words "brain," "user," "mind," "machine," "computer," "communication," "interface," "BMI," and "BCI" were used, and the results were ranked by the total citation number. The terms "neural prosthetics" and "neuroprosthetics" were also used as search terms, in order to exclude some prosthetics that are only linked to other parts of the nervous system, such as the peripheral nerves, while the term BCI usually designates an interface with the central nervous system [8]. The full texts of these reports were mainly obtained from PubMed, EMBASE, and Medline. When full-text articles were not available, online abstracts were used.

Data inclusion criteria were as follows: (a) peer-reviewed articles on BCI research published and indexed in the Web of Science and (b) original research articles and review articles. Exclusion criteria were (a) patents, books, manuals, and non-biomedical publications, and (b) conference abstracts and case reports.

The 100 most highly cited articles were then identified based on the number of citations, and those published in the past 2 years were also considered. Owing to differences in time since publication, annual citations rates were also defined. Articles were selected by reading the abstract to gauge whether they were related to BCI, and the following data were extracted from each of the articles: title, year of publication, last correspond author and his/her first institution, country of origin, journal name, number of citations, type of study, research topic and keywords of study.

Statistical analysis was performed using R version 3.2.3 (Wooden Christmas-Tree). Statistically significant differences were identified using a non-parametric ANOVA analysis with an alpha level of 0.05. CiteSpace version 4.0 was used to visualize trends and patterns in BCI research [14–16].

3. Results

The 100 most highly cited articles on BCI research in Web of Knowledge were listed in Supplemental Materials (Table S1) in descending order of the total citation numbers they have. The 100 papers obtained a mean of 137.1 (SE 15.38) citations per article, the top one received 1294 citations (Hochberg, LR et al., 2006, *Nature*) [17]. Annually, the 100 highly cited articles received average 19.45 (SE 1.92) citations per paper (range, 5.40 to 129.40).

3.1. Countries and institutions of origin

The 100 articles originated from 16 different countries (Fig. 1); most (n = 48) studies were from the USA, followed by Germany (n = 19). Five studies were from Singapore; four from Switzerland and Austria; three each from France, England, Canada, and China; and one each from Sweden, Spain, the Netherlands, Japan, Israel, and Italy. Even though we used no language restrictions, all 100 studies were published in English.

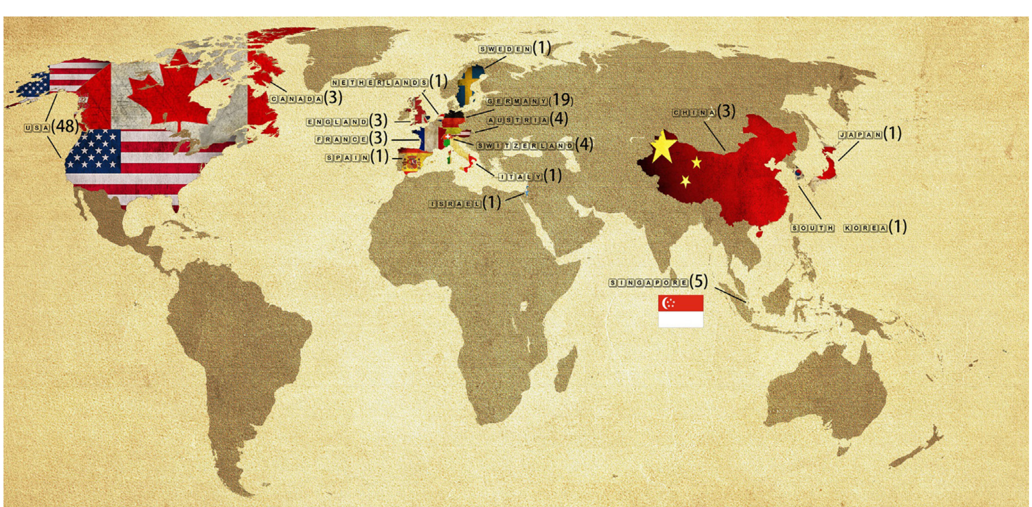

Fig. 1. Distribution of countries from which the 100 most highly cited brain-computer interface research articles originated from 2006 to 2015.

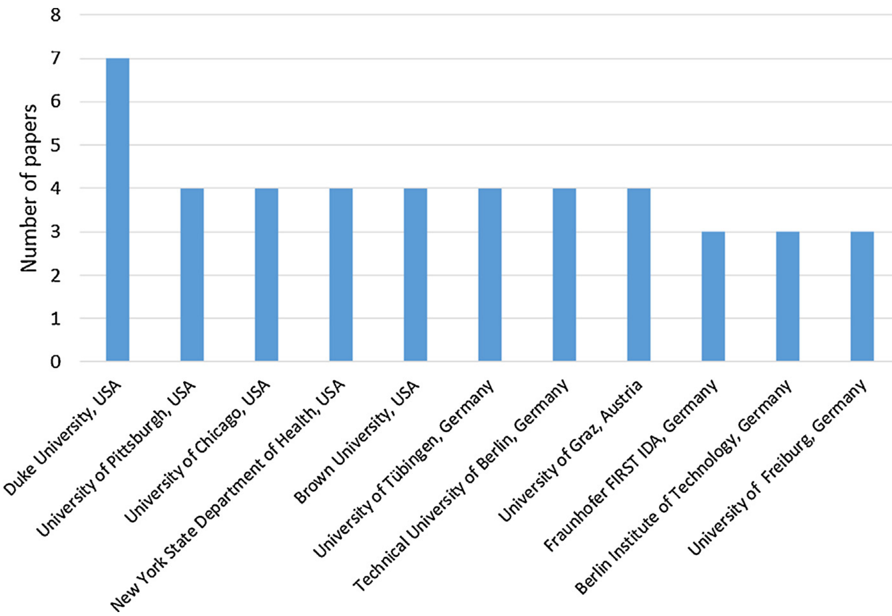

Fig. 2. Institutions contributing the most highly cited brain-computer interface research articles from 2006 to 2015.

Table 1
The journals in which the 100 most highly cited brain – computer interface articles were published from 2006 to 2015; the journal impact factor was based on Thomson Reuters Web of Knowledge Journal Citation Reports Ranking (2015).

Rank	Journals	N	IF
1	*IEEE Transactions on Biomedical Engineering*	12	2.347
2	*Journal of Neural Engineering*	8	3.295
2	*Journal of Neuroscience*	8	6.344
3	*Clinical Neurophysiology*	5	3.097
3	*Journal of Neurophysiology*	5	2.887
3	*Nature*	5	41.456
7	*Journal of Neuroscience Methods*	4	2.025
7	*Neuroimage*	4	6.357
9	*Nature Neuroscience*	3	16.095
	Others	46	

IF, impact factor.

These articles originated from 57 universities, hospitals, and clinics; 20 institutions were responsible for two or more of these articles, led by Duke University ($n = 7$). The 10 research institutions with the highest number of highly cited articles are listed in Fig. 2.

3.2. Journal distribution and study field

The top 100 highly cited articles were published in 45 journals; most appeared in the *IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING* ($n = 14$), followed by the *JOURNAL OF NEURAL ENGINEERING* and the *JOURNAL OF NEUROSCIENCE* ($n = 8$) (Table 1). *THE LANCET* (n = 1) was the most high impact journal in the list [18].

3.3. Study fields

Neuroscience, neurology, and engineering are the most BCI-related areas (Fig. 3). Keywords of BCI articles occur in categories including “machine learning,” “neural control,” “visual attention,” “human brain mapping,” and “disabled subject” (Fig. 4).

Of the 100 articles, 72 were original articles and 28 were review articles. Original articles were classified based on the experimental subjects; 31 articles used human trials (Table 2), 18 articles used nonhuman primate trials (Table 3). Cats and rats were used as experimental subjects in one paper. Highly cited articles focusing on human trials had more average citation numbers (167.81,

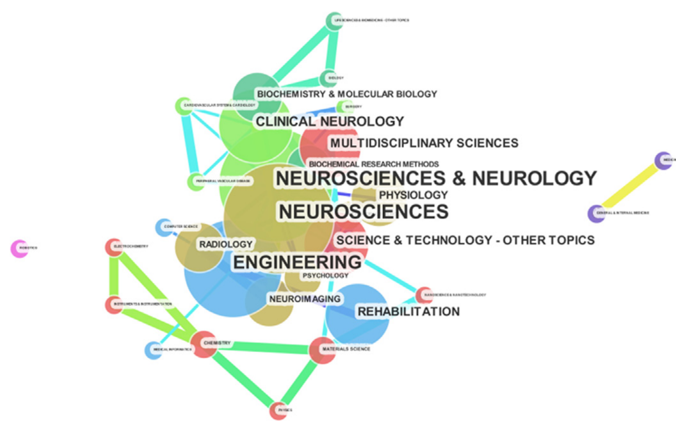

Fig. 3. Co-subject analysis of brain-computer interface research field distribution in the Web of Science category during 2006–2015.

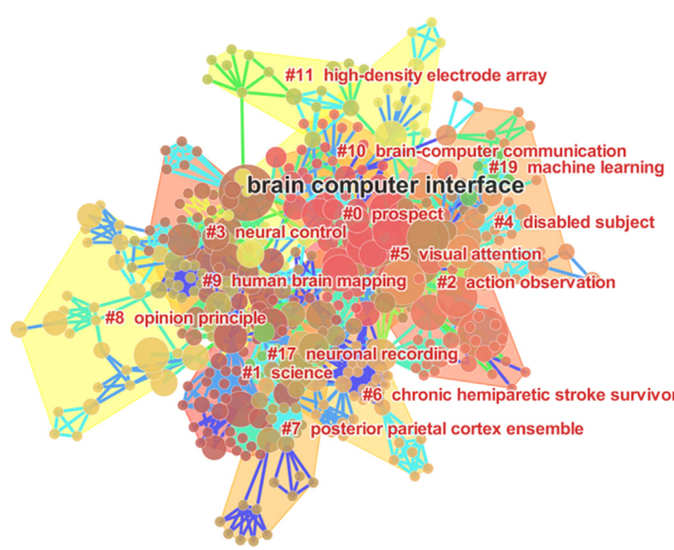

Fig. 4. Visualization analysis of co-keywords burst terms in brain-computer interface research articles between 2006 and 2015 retrieved from the Web of Science.

Table 2
The top 10 highly cited brain–computer interface research articles involving human trials from 2006 to 2015.

Titles	Journal	Year	Citation Numbers		
			Total	Annual	Past 2 years
Neuronal ensemble control of prosthetic devices by a human with tetraplegia	*Nature*	2006	1294	129.4	245
Reach and grasp by people with tetraplegia using a neurally controlled robotic arm	*Nature*	2012	391	97.75	247
The non-invasive Berlin Brain – Computer Interface: Fast acquisition of effective performance in untrained subjects	*Neuroimage*	2007	250	27.78	52
An efficient P300-based brain – computer interface for disabled subjects	*Journal of Neuroscience Methods*	2008	234	29.25	67
High-performance neuroprosthetic control by an individual with tetraplegia	*Lancet*	2013	229	76.33	179
Temporal classification of multichannel near-infrared spectroscopy signals of motor imagery for developing a brain – computer interface	*Neuroimage*	2007	226	25.11	65
Decoding two-dimensional movement trajectories using electrocorticographic signals in humans	*Journal of Neural Engineering*	2007	203	22.56	47
Single-trial analysis and classification of ERP components – A tutorial	*Neuroimage*	2011	199	39.8	105
Flexible, foldable, actively multiplexed, high-density electrode array for mapping brain activity in vivo	*Nature Neuroscience*	2011	196	39.2	118
Evaluation of robotic training forces that either enhance or reduce error in chronic hemiparetic stroke survivors	*Experimental Brain Research*	2006	169	16.9	29

Table 3
The top 10 highly cited brain–computer interface research articles with nonhuman primate trials from 2006 to 2015.

Titles	Journal	Year	Citation Numbers		
			Total	Annual	Past 2 years
Cortical control of a prosthetic arm for self-feeding	*Nature*	2008	640	80	163
Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics	*Nature Materials*	2010	344	57.33	165
Direct control of paralyzed muscles by cortical neurons	*Nature*	2008	227	28.38	67
Predicting movement from multiunit activity	*Journal Of Neuroscience*	2007	119	13.22	32
Active tactile exploration using a brain – machine – brain interface	*Nature*	2011	132	26.4	77
Congruent activity during action and action observation in motor cortex	*Journal of Neuroscience*	2007	117	13	29
Functional network reorganization during learning in a brain – computer interface paradigm	*PNAS*	2008	106	13.25	46
Decoding trajectories from posterior parietal cortex ensembles	*Journal of Neuroscience*	2008	105	13.13	31
A high-performance neural prosthesis enabled by control algorithm design	*Nature Neuroscience*	2012	80	20	58
Long-term asynchronous decoding of arm motion using electrocorticographic signals in monkeys.	*Frontiers in Neuroengineering*	2010	77	12.83	27

SE 22.35) than those focusing on nonhuman primate trials (135.84, SE 14.02), but the difference was not significant ($P = 0.5791$). The other 21 original articles dealt with the design and development of algorithms, recordings, or techniques related to BCI, without direct investigation of subjects.

4. Discussion

With technological and conceptual advances, the field of BCI has exponentially grown during the past 10 years, and currently involves a variety of specialties. Thus, in contrast to other research fields in which most of the highly cited articles are published in only a few journals [5,19], the articles pertaining to BCI were published in 34 different journals, reflecting the multidisciplinary nature of BCI research.

The 100 most highly cited articles from the past 10 years were cited 53 – 1249 times. This number is considerably higher than citations in limb prosthetics studies, in which studies received 11 – 90 citations [8], even though those studies were published over longer time periods (1980 – 2012). This observation is not surprising, given the important applications of BCI; some fields of BCI research are typically focused on neural prosthetics aimed at recovering loss of motor function, sight, and hearing. Moreover, BCI is also a powerful tool for exploring fundamental questions in neuroscience, while BCI experiments can also be considered as direct or indirect observations of neurophysiological activity in the brain, and can shed light on how information is encoded and decoded by neural circuits in real time, and how this coding changes with neural plasticity [20].

Our study found that most of the 100 highly cited articles originated from the USA, which is similar to other fields of research [21,22]. Furthermore, half of the institutions from which these papers originated are located in the USA. These findings prove the USA's overwhelming impact on BCI research, because of its large population and the abundant financial resources available to the world of science [23].

The article from our top 100 list that had received the most citations was a human BCI study, published in *Nature* in 2006, written by Hochberg and colleagues, with correspondence directed to John P. Donoghue at Brown University [17], in which the authors described the early results of neural motor prostheses investigations, based on intracortical neuronal ensemble spiking activity for restoring independence in humans with paralysis. This article received 245 citations over the past 2 years (2014 and 2015), and was ranked second among the 100 papers, and was also ranked first among the annual citations, with 129.4 citations per year.

Their work continued, with a paper published in *Nature* in 2012 [24], which ranked 5th overall (2nd annually and 1st in the past 2 years), demonstrated that two people with long-standing tetraplegia from cortical neuronal ensemble signal-based control of a robotic arm to perform three-dimensional reach and grasp movements. Their results showed the feasibility to recreate useful multidimensional control of complex devices directly from a small sample of neural signals in people with tetraplegia, years after injury to the central nervous system.

The most highly cited article involving nonhuman primate trials was also published in *Nature* [25] in 2008, written by Velliste and colleagues, with correspondence addressed to Andrew B. Schwartz, and originating from the University of Pittsburgh. This paper ranked 2nd overall (3rd annually and 5th of the past 2 years). It used intracortical microelectrode arrays implanted in the motor cortex of monkeys to record populations of neuronal spiking activity for controlling a mechanized arm replica in a self-feeding task, with a view to developing dexterous prosthetic devices that could ultimately achieve arm and hand function at a near-natural level. In 2013, these authors transferred the trial to a human with tetraplegia, using two 96-channel intracortical microelectrodes in the motor cortex. The participant was able to use the prosthetic limb to perform skillful and coordinated reach and grasp movements, and this landmark work was published in *THE LANCET*; it was also the latest published article among the top-100 papers.

IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING and the *JOURNAL OF NEURAL ENGINEERING* published most of the highly cited articles; these two journals are associated with the subject category of biomedical engineering, which in many ways is the cornerstone of BCI. Given that several high impact factor journals have subordinate serials, the impact of a particular journal family is even greater. For example, if the number of such papers in all the *Nature* serials are combined, including *NATURE (n = 5), NATURE NEUROSCIENCE (n = 3), NATURE COMMUNICATIONS (n = 1), NATURE MATERIALS (n = 1), NATURE REVIEWS NEUROSCIENCE (n = 1),* it would comprise 12 articles in total. Additionally, half of the top-10 highly cited papers were published in *Nature* and its subordinate serials; thus, as one of the top-3 basic science journals, along with *CELL* and *SCIENCE, NATURE* appears to have a greater interest in the BCI field.

Co-keywords and study category analysis showed that advancement in BCI research involves not only the development of neural prosthetics; but also attempts at understanding brain function by encoding and decoding neural signals and activities. BCI can be a bridge between engineering and neuroscience [20]; yet; to move forward; a number of issues need to addressed; such as improving the quality of neuronal recordings; achieving stable; long-term performance; and extending the BCI approach to a broad range of motor; sensory; and even cognitive functions [26–29].

This study has several limitations, as do other bibliometric analysis. First, older studies had more time to accumulate citations [30], articles that were published more recently will have a shorter exposure to the scientific community [31]. In an attempt to control for this potential bias, we utilized annually citations analysis and recent 2 years citations. Second, although we attempted to be as inclusive as possible, some studies were excluded in a subjective manner, and it may be possible that other relevant highly cited articles were missed. Third, all articles were confined to English journals; language barriers are known to create a bias in citation rates as authors are more likely to cite articles in their own language [32,33]. Fourth, factors potentially influencing citation rates, such as journal and author self-citations, were not considered [34]. Lastly, it should be acknowledged that the number of times an article has been cited does not directly reflect its quality [35].

In conclusion, our analysis provides a review of landmark papers published in the field of BCI; these 100 highly cited articles reflect major advances and hot topics of the past 10 years, which can help to distinguish incremental from transformational studies, and provide insights into priorities and trends in BCI research that could serve as sources for future research directions.

Conflicts of interest

The authors declare no competing financial or personal interests.

Contributors

Kejia Hu, Ziv Williams and Wendong Xu designed the study, Kejia Hu, Chao Chen, and Qingyao Meng performed the search and collect the data, Kejia Hu performed the analyses, Kejia Hu, Ziv Williams and Wendong Xu wrote the manuscript. All authors read and approved the manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.neulet.2016.10.022.

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