Quantifying and visualizing the transcranial direct current stimulation research indicators

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ABSTRACT

The field of transcranial direct current stimulation (tDCS) has experienced significant growth in the past 15 years which is mainly devoted to determining the basic and clinical potential of tDCS in humans. The aim of this study is to quantitatively analyze the current worldwide progress on tDCS research as well as to highlight researchers, journals, institutions and countries which are contributing significantly in the past 18 years. We conducted a quantitative analysis of research articles regarding tDCS published from 1998 to 2016 and indexed in the web of science core collection database. Data was downloaded in October, 2016. In the past 18 years, there were 2457 studies on tDCS indexed by web of science database, including all documents type such as article, review, meeting abstract, proceedings paper, letters, and etc. This study is focusing on the main articles and reviews; therefore, the research production was reduced to 2000 publications. The analysis showed that most of the studies in the field were published by North American and European institutions with a reasonable proportion of the publications were also by Japanese institutions from Asia. From the perspective of research progress, we found that the number of published papers on tDCS has increased significantly in the past 10 years, between them a remarkable positive correlation exists.

Keywords: Bibliometric analysis, Bibliometric indicators, Rehabilitation, Reviews, TDCS, Treatment, Web of science

INTRODUCTION

Noninvasive stimulation of the brain has become extensively applicator in the past two decades in research and it had shown its valuable potential therapeutic effect in cognitive neuroscience, neurophysiology, psychiatry, and neurology. There are two applications neuromodulation of this modality which are transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS). TMS works on neuro-stimulation and neuro-modulation, while tDCS is a purely neuromodulator.1 tDCS is a safe non-invasive brain stimulation that consists of a current generator and two electrodes, an active electrode is placed on the target area of stimulation of the scalp and a reference electrode over the contralateral area which can deliver weak direct currents in brain.2 The low cost and simplicity in technique has guided interest in potential basic and clinical applications which showed promising results in cognitive enhancement and physical performance.3 One of the major areas of interest is the enhancement of memory function in healthy individuals.
tDCS delivers either cathodal or anodal current to the brain cortex directly. Cathodal stimulation type is negatively-charged current which is proven in animal studies to decrease the stimulation and cause hyperpolarization, while anodal stimulation increase resting membrane to become more positive. In human, these two different types of stimulation showed distinct effect. Anodal stimulation can increase blood-oxygen level-dependent (BOLD) signal in the fMRI where cathodal stimulation decreases it. These properties of the tDCS can help us to understand the brain physiology and treating various conditions of brain’s diseases. The influence of the excitability can be altered depending on the level of intensity, the site of the stimulation, the performed task during stimulation and also there is a variability from session to session within the same individual.

Bibliometrics is a research field that studies the bibliographic material in a quantitative way and assesses the impact of scientific contributions. It is very useful in analyzing research area and identifies its leading trends. Bibliometric can be developed in a wide range of contexts including the analysis of a research topic, journals, institutions and countries. These bibliometric research studies enable researchers and specialists to analyses a specific research field by highlighting influential articles, journals, authors, institutions and countries. This countenances researchers to have an understanding of the research field and think beyond existing contributions.

Motivated by this, the aim of this research study is to depict bibliometric view of the scientific research indicators on the tDCS between 1998 and 2016, which has indicated that tDCS research is attaining substantial attention recently from researchers, academicians and professionals. Furthermore; the main advantage of this study is that one can comprehend who is leading and contributing significantly in the tDCS research and what are the main trends emerging in recent years which have influenced even more? Bibliometric research study in this regard; analyses published articles, citations and their sources of information. Moreover, this study also utilizes the VOS viewer software to visualize relations between authors and organizations, such as co-authorship in the tDCS research through bibliographic couplings and co-citation analysis. There have been many studies published recently concerning bibliometrics and networks mapping analyses, however, with the best of our knowledge no such study is found for the tDCS research area in the scientific research literature.

The rest of the paper is structured as follows. Section 2 briefly reviews the bibliometric methods used in the analysis. Section 3 presents the publication and citation structure of the all tDCS results in the WOS. Section 4 develops a mapping and research networks analysis of the all tDCS articles in the WOS by using the VOS viewer software. Section 5 summarizes the main findings and conclusions of the paper.

**REVIEW OF LITERATURE**

Authors collected data from the web of science database on tDCS to provide an understanding of international research trends over the past 18 years using bibliometric indicators. Recent research indicators would be reflected in its publication outputs. It has also been pointed out that citation rate is not only a direct measure of the impact or importance of a particular scholarly work, but also provides a marker of its recognition within the scientific community. A common research tool for this analysis is the bibliometric method, which has already been widely applied in many disciplines of management, science and engineering areas. Using bibliometric analysis such as citation rates of top-cited articles reveal useful and interesting information about scientific progress in a research field. Several recent studies have identified and analyzed citation classics and top-cited articles in various fields of science and engineering.

Although there are a wide range of methodologies that can be implemented when developing a bibliometric review; however, this study focuses on a general overview that presents different research indicators so each reader can get its own understanding of the bibliometric analysis. The main reason for this is that there exists no single method that everyone agrees upon as the unique method to be applied to evaluate research. The key problem is that some people may prefer to focus on some bibliometric indicators while the others may prefer some other influential indicators. However; specifically, it is clear that the comparison between productivity and influence is measured with the number of publications and citations. Some authors may give more importance to productivity and vice versa. Therefore, each method may evaluate the data in a different way. An alternative to get a unified method could be through the use of a consensual process where everybody agrees on the importance of each variable. However, this would be a subjective method because it is mainly based on the opinion of some experts in the field. To provide a detailed overview of the data, this study analyzes the total number of publications and citations, the citations per paper, the H-index The H-index is a measure that aims to represent the importance of a set of papers. It combines papers with citations. For example,
if a set of papers have an H-index of 20; this means 20 of the papers included in the set have received at least 20 citations each. Note that since its introduction, the H-index has been extended and generalized by many authors. As mentioned earlier; this research study analyzes the Web of Science (WOS) data which is currently owned by Clarivate analytics, there are many databases containing these informative data. This work considers only web of science core collection, which considers several sub databases, containing the conference proceedings citation index. Web of science core collection includes research mostly from all well-known fields, which currently includes databases of more than 15,000 journals and 60,000,000 papers. WOS provides categorization of the contents according to 251 subject categories and in 151 research areas. As mentioned earlier this research is depending only on the web of science, although there are other databases such as Scopus and Google Scholar which are not considered here in this study.

Defining an appropriate search scheme is an important step in any such study. In this research; “Transcranial Magnetic Stimulation” has been used as keywords to develop the search process with option “Topic” in the search section. This search has collected all the articles belonging to “Transcranial Magnetic Stimulation” field. However, this kind of search process will bring some articles which have used this keyword but it does not belong to the scope of this research study. After carefully reviewing, such articles have been omitted. Note that WOS only includes the journal since 1987.

DISCUSSION

Publication and citation evolution of tDCS

tDCS methods started publishing papers in 1998. In the last few years it increased publication dramatically. According to WOS records; Figure 1 shows the evolution of the number of papers (Y-axis) published annually. As we can see, the number of papers starts increasing from 2008 onward with an exponential increase from 2011. One may visualize that this growth is due to the increased number of researchers worldwide as well as due to inclusion of the new journals in the WOS, the average citations received in each year is increasing throughout the selected time period of this research study.

| Table 1: General citation structure in tDCS research. |
|-------------------------------------------------------|
| Number of Citations (NOC) | Number of papers | % of category in total |
|----------------------------|------------------|------------------------|
| NOC < 50                   | 1690             | 86.62                  |
| 50 ≤ NOC < 100             | 160              | 8.2                    |
| 100 ≤ NOC < 500            | 96               | 4.92                   |
| 500 ≤ NOC                  | 5                | 0.26                   |
| Total                      | 1951             | 100                    |

There are a number of abbreviations which are used by the WOS. Without having knowledge of them, it is difficult to follow-up the results and analysis of this research study. Table 1 presents all the abbreviations used in this research study.

Table 2 illustrates a broader picture of the citation status in the field of tDCS research. It depicts a general citation structure of all the papers, which categorizes the articles according to the times of citations they have received, with the percentage of every category.

Note that a bit more than 0.26% of the articles have received more than 500 citations, about 4.92% receive at least more than 100 citations and 8.2% of the articles received more than 50 citations; whereas more than 86% of all results have been cited less than 50 times.

Most influential and productive journals

tDCS research articles are being published in various and high number of journals listed in the WOS. Table 3 provides information regarding the influential journals. Top 30 influential journals are sorted in Table 3 by the number of research articles published in the field of tDCS. Brain Stimulation Journal is the top most productive and influential journal based on total number of publications (155), total number of citation (4658) as well as H-index criterion. Journal of Physiology London although ranked 14 with H-index; however, it has obtained the 2nd highest number of citations (3117) among the top 30 selected journals. To present the most interested journals in tDCS; Table 3 also contains a column (%TP) showing the percentage of tDCS papers published in a journal with respect to total number of papers in the same journal. According to TP% indicator, Brain Stimulation journal again ranked top (17%) followed by Frontiers in Human Neuroscience (19.6%) and Neuro-rehabilitation and Neural Repair (1.75%) respectively.

Further; we consider the most productive and influential journals keeping in view BIs criterion of TP, H-index, TC, % TP and the number of articles with more than 50 citations throughout the selected time period. A list of the most productive and influential journals and their ranking with respect to each selected BIs is presented in Table 4. Ranking is based on tDCS research only.

Table 4 illustrates that Brain Stimulation (BS) Journal is the only journal which maintains its highest rank among all selected BIs except %TP; Journal of Neuroscience which is ranked the top most influential journal with the number of articles having more than 50 citations throughout the selected period. In addition; among the list of most influential journals (Table 4), six journals (BS, FHN, PO, NL, CN and JN (based on citations >50) are considered as top most productive journals in this field of tDCS research study.
Table 2: Most influential journals.

| Rank | Journal name | tDCS Research | Impact factor | All publications |
|------|--------------|---------------|---------------|-----------------|
|      | H | TP | TC | %TP | >500 | >100 | >50 | TP | TC | H |
| 1    | BS | 34 | 155 | 4658 | 17 | 1 | 7 | 14 | 4.79 | 912 | 10881 | 43 |
| 2    | FHN | 16 | 78 | 775 | 1.96 | 0 | 0 | 1 | 3.63 | 3988 | 28924 | 51 |
| 3    | PO | 17 | 66 | 866 | 0.04 | 0 | 1 | 2 | 3.06 | 164623 | 1256490 | 190 |
| 4    | NL | 18 | 62 | 1032 | 0.19 | 0 | 1 | 5 | 2.11 | 32348 | 746568 | 199 |
| 5    | NI | 25 | 54 | 1907 | 0.37 | 0 | 1 | 14 | 5.46 | 14692 | 626975 | 268 |
| 6    | CN | 21 | 54 | 2361 | 0.92 | 0 | 3 | 9 | 3.43 | 5880 | 139941 | 134 |
| 7    | NP | 17 | 52 | 1215 | 0.62 | 0 | 4 | 5 | 2.99 | 8324 | 330602 | 198 |
| 8    | JN | 24 | 47 | 2624 | 0.14 | 0 | 9 | 15 | 5.92 | 34103 | 2511583 | 433 |
| 9    | EJN | 18 | 46 | 1548 | 0.26 | 0 | 4 | 6 | 2.98 | 17840 | 412825 | 181 |
| 10   | EBR | 18 | 45 | 1629 | 0.31 | 0 | 4 | 6 | 2.06 | 14680 | 501882 | 215 |
| 11   | RNN | 17 | 44 | 1075 | 3.62 | 0 | 3 | 3 | 2.66 | 1214 | 18992 | 58 |
| 12   | JNP | 17 | 27 | 952 | 0.14 | 0 | 1 | 3 | 2.65 | 19581 | 1044229 | 313 |
| 13   | JCN | 10 | 27 | 1187 | 0.34 | 0 | 4 | 4 | 3.56 | 7850 | 178302 | 181 |
| 14   | NR | 12 | 26 | 1001 | 0.22 | 0 | 3 | 2 | 1.34 | 11802 | 322218 | 170 |
| 15   | BBR | 7 | 24 | 328 | 0.22 | 0 | 0 | 2 | 3 | 10902 | 265864 | 159 |
| 16   | JPL | 15 | 20 | 3117 | 0.03 | 1 | 5 | 2 | 4.73 | 62649 | 1889456 | 391 |
| 17   | NNR | 13 | 20 | 595 | 1.75 | 0 | 2 | 2 | 4.04 | 1146 | 25268 | 68 |
| 18   | CC | 11 | 19 | 762 | 0.43 | 0 | 2 | 5 | 8.29 | 4432 | 245373 | 202 |
| 19   | NS | 7 | 19 | 178 | 0.09 | 0 | 0 | 1 | 3.23 | 22258 | 874971 | 267 |
| 20   | IJN | 10 | 18 | 668 | 0.19 | 0 | 3 | 0 | 4.33 | 9474 | 38056 | 76 |
| 21   | C | 9 | 18 | 204 | 0.47 | 0 | 0 | 2 | 3.57 | 3805 | 86200 | 103 |
| 22   | JAD | 9 | 16 | 362 | 0.18 | 0 | 2 | 5 | 3.57 | 9000 | 210199 | 144 |
| 23   | FN | 3 | 15 | 19 | 0.72 | 0 | 0 | 0 | 3.4 | 2071 | 11370 | 36 |
| 24   | NH | 5 | 14 | 81 | 0.87 | 0 | 0 | 0 | 1.45 | 1602 | 13067 | 43 |
| 25   | JPT | 4 | 14 | 54 | 0.51 | 0 | 0 | 0 | 0.39 | 2721 | 5246 | 13 |
| 26   | T | 3 | 14 | 14 | 0.47 | 0 | 0 | 0 | 1.86 | 2973 | 17519 | 41 |
| 27   | JE | 7 | 13 | 133 | 0.74 | 0 | 0 | 0 | 1.83 | 1764 | 11694 | 42 |
| 28   | NM | 6 | 13 | 138 | 0.85 | 0 | 0 | 0 | 2.41 | 1526 | 837 | 36 |
| 29   | FP | 4 | 13 | 111 | 0.18 | 0 | 0 | 0 | 2.46 | 7360 | 27212 | 47 |
| 30   | FCN | 3 | 13 | 45 | 0.79 | 0 | 0 | 0 | 4.61 | 1642 | 10724 | 36 |

Table 3: Selecting the most productive and influential journals.

| Rank | TP | H-index | TC | %TP | >50 |
|------|----|---------|----|-----|-----|
| 1    | BS | BS | BS | BS | JN |
| 2    | FHN | NI | JPL | RNN | BS |
| 3    | PO | JN | JN | FHN | NI |
| 4    | NL | CN | CN | NNR | CN |
| 5    | CN | EBR | NI | CN | EJN |
| 6    | NI | EJN | EBR | NH | EBR |
| 7    | NP | NL | EJN | NM | NL |
| 8    | JN | NP | NP | FCN | NP |
| 9    | EJN | RNN | JCN | JE | CC |
| 10   | EBR | JNP | RNN | FN | JCN |

Another important and common BI measure to assess the quality of a journal is the impact factor. Impact factor (IF) basically is an indicator of the journal value, which is calculated by dividing the number of citations received in the last two years (i.e. n-1 and n-2 which is “TC2” in Table 4, Figure 1) from year n divided by the total number of papers published in the last two years (n-1 and n-2 which is “TP2” in Table 4).

Table 4: Impact factor in tDCS research.

| Year | TP | TC | TC2 | TP2 | IF |
|------|----|----|-----|-----|----|
| 2006 | 21 | 3051 | 208 | 27 | 7.703 |
| 2007 | 27 | 3126 | 206 | 29 | 7.93 |
| 2008 | 54 | 4969 | 365 | 48 | 7.604 |
| 2009 | 60 | 3953 | 480 | 81 | 5.926 |
| 2010 | 72 | 3938 | 711 | 114 | 6.237 |
| 2011 | 145 | 6223 | 999 | 132 | 7.568 |
| 2012 | 176 | 5151 | 1216 | 217 | 5.604 |
| 2013 | 266 | 4863 | 2269 | 321 | 7.069 |
| 2014 | 283 | 3354 | 2395 | 442 | 5.419 |
| 2015 | 429 | 1902 | 3152 | 549 | 5.741 |
exponential growth models with $R^2 = 0.9902$ and $R^2 = 0.9848$ in Figure 2 and 3 are illustrated in the following equations respectively.

$Y \text{ (publications)} = 17.295e^{0.356x}$ (1)

$Y \text{ (citations)} = 133.12e^{0.326x}$ (2)

**Most influential articles**

To focus on important and influential articles published in the tDCS research field, all the articles have been sorted according to the number of citations received. The more the citations received by an article the more important and influential it is in the respective field. The articles with new and innovative ideas always receive higher number of citations. Table 6 shows the 50 most cited articles of all time in tDCS research. Nitsche al has the most cited paper (1430 citations) which was published in 2000 and analysed tDCS excitability changes induced in the human motor cortex by weak transcranial direct current stimulation (40). Second top cited (841 citations) article (which is one of the safety paper about tDCS) followed by the 3rd top cited article (782 citations) belongs to Nitsche et al as well. Fourth (549 citations) and fifth (536 citations) most cited papers are by authors Gandiga et al and by Hummel et al respectively.41,42

Figure 4 showed analysing the citations on yearly basis (C/Y); it is worth noting that Nitsche et al, has received the highest number of citations (98) in 2008 followed by Nitsche et al article; which has received 89 citations in 2000; whereas articles and by Stagg; et al in 2011 and by Brunoni et al in 2012 have received 66 citations respectively.46,42,56,66

**Most productive and influential authors**

As mentioned earlier, tDCS research is very active in recent years and a number of authors and researchers are contributing significantly. In order to determine which authors have the highest influence and presence; Table 7 shows the 40 most active authors contributing to the field with having more than 15 research articles. The ranking (R) in Table 7 is done according to the number of total citations (TC) received by each article in the tDCS research, however; the criterion for the selection of influential authors is that only those authors which have published more than 15 articles are included in the list.

Nitsche MA is the most influential (14538 citations) author followed by Paulus W and Fregni F which have received the 2nd and 3rd positions by having number of citations 13376 and 8529 respectively. However, it is worth noting that Fregni F is the most productive author among the selected list based on number of publications (TP = 169) published in the tDCS field.
It is also worth noting that even Pascual-Leone A and Boggio PS have published the same number of articles; however, Pascual-Leone A has received higher number of citations (6663) as compared to Boggio PS (5281)

| R | J   | TC | Author/s          | Year | C/Y |
|---|-----|----|-------------------|------|-----|
| 1 | JPL | 1430| Nitsche et al     | 2000 | 89  |
| 2 | N   | 841 | Nitsche et al     | 2001 | 56  |
| 3 | BS  | 782 | Nitsche et al     | 2008 | 98  |
| 4 | CN  | 549 | Gandiga et al     | 2006 | 55  |
| 5 | B   | 536 | Hummel et al      | 2005 | 49  |
| 6 | B   | 495 | Liebetanz et al   | 2002 | 35  |
| 7 | JPL | 457 | Nitsche et al     | 2003 | 35  |
| 8 | PNA | 435 | Reis et al        | 2009 | 62  |
| 9 | EBR | 400 | Fregni F et al    | 2005 | 36  |
| 10| JCN | 375 | Nitsche et al     | 2003 | 29  |
| 11| JN  | 373 | Siebner et al     | 2004 | 31  |
| 12| NR  | 367 | Fritsch et al     | 2010 | 61  |
| 13| BRB | 363 | Poreisz et al     | 2007 | 40  |
| 14| LN  | 334 | Hummel et al      | 2006 | 33  |
| 15| NS  | 332 | Stagg et al       | 2011 | 66  |
| 16| EJN | 323 | Lang N et al      | 2005 | 29  |
| 17| NCP | 300 | Fregni et al      | 2007 | 33  |
| 18| CN  | 298 | Miranda et al     | 2006 | 30  |
| 19| JPL | 290 | Nitsche et al     | 2005 | 26  |
| 20| CN  | 286 | Nitsche et al     | 2003 | 22  |
| 21| NR  | 283 | Fregni F et al    | 2005 | 26  |
| 22| JN  | 280 | Nitsche A et al   | 2007 | 31  |
| 23| P   | 278 | Fregni F et al    | 2006 | 28  |
| 24| BS  | 275 | Datta et al       | 2009 | 39  |
| 25| ARP | 273 | Wagner et al      | 2007 | 30  |
| 26| BS  | 263 | Brunoni et al     | 2012 | 66  |
| 27| RNN | 234 | Boggio S et al    | 2007 | 26  |
| 28| JN  | 228 | Stagg et al       | 2009 | 33  |
| 29| JNS | 227 | Boggio S et al    | 2006 | 23  |
| 30| BS  | 225 | Ziemann et al     | 2008 | 28  |
| 31| NI  | 217 | Wagner et al      | 2007 | 24  |
| 32| AR  | 207 | Fregni et al      | 2006 | 21  |
| 33| EBR | 204 | Jacobson et al    | 2012 | 51  |
| 34| JN  | 202 | Marshall et al    | 2004 | 17  |
| 35| S   | 194 | Baker et al       | 2010 | 32  |
| 36| JIN | 187 | Boggio et al      | 2008 | 23  |
| 37| JN  | 187 | Fecteau et al     | 2007 | 21  |
| 38| BP  | 182 | Lang N et al      | 2004 | 15  |
| 39| N   | 181 | Lindenberg et al  | 2010 | 30  |
| 40| JNN | 177 | Monti A et al     | 2008 | 22  |
| 41| JPL | 175 | Ardolino et al    | 2005 | 16  |
| 42| JCN | 174 | Antal et al       | 2004 | 15  |
| 43| JOV | 174 | Antal A. Nitsche et al | 2004 | 15 |
| 44| JIN | 173 | Brunoni et al     | 2011 | 25  |
| 45| CC  | 167 | Joseph M et al    | 2011 | 33  |
| 46| RNN | 167 | Nitsche et al     | 2011 | 33  |
| 47| JN  | 131 | Fecteau et al     | 2007 | 15  |
| 48| NP  | 160 | Kincses TZ et al  | 2004 | 13  |
| 49| PO  | 159 | Zaehle et al      | 2010 | 27  |
| 50| JCN | 157 | Floeel et al      | 2008 | 20  |
citations). It is worth noting too that the four most productive and highly cited authors (Nitchi MA, Paulus W, Fregni F and Pascual-Leone A) have more than 43000 citations in WOS which implies that they are very highly ranked in the tDCS research field worldwide. It is also noted that most of the influential and productive authors (62.5 %) are working in Germany, USA and Australia only.

![Figure 2: Publications trend analysis.](image)

![Figure 3: Citations trend analysis.](image)

![Figure 4: Authors published papers in transcranial direct current stimulation field.](image)

Next, let us look into the productivity of the leading authors throughout the selected time period in the top most productive list of six (refer Table 4) journals. For doing so, Table 8 presents the evolution of the publications of the most productive authors in the tDCS appeared in the top selected journals. In Table 8, we have selected only those ten influential authors which have published ten or more than 10 articles in the selected list of eight influential journals. Figure 5 provides an overview of the authors which are focusing on specific journals to publish their research articles and those who tend to publish in various scientific journals.

![Figure 5: Authors published papers in transcranial direct current stimulation field and link between organizations.](image)

Results reveal that the top three authors (Fregni F, Nitchi MA and Paulus W) maintain their leading publishing position in the tDCS research as well as have published in all six selected journals; however, their highest number of articles are published in the BSJ journal. Next to them is Bikson M, who holds the fourth position and also publish in all the selected journals with the highest number of articles published in the BS journal too. This has strong evidence that most of the influential authors are publishing their work in the Brain Stimulation journal.

**Most influential institutions in tDCS research**

tDCS research is conducted by several leading institutions. Many of these institutions are productive and influential because the leading authors and researchers are working in these institutions. However, sometimes, there are some institutions which maintain a long list of productive and leading authors making them more influential.

A list of twenty-five (25) most influential and productive institutions in tDCS research is presented in Table 9 which are ranked according to the total number of article’s citations published in six selected journals by...
these institutions. Figure 6 showed the last three columns also provide other bibliometric information (TP, TC and H-index) regarding all tDCS research articles published elsewhere in the WOS.

### Table 6: Most influential authors in tDCS research.

| R | Name          | Country  | tDCS | All |
|---|---------------|----------|------|-----|
|   |               |          | TP   | TC  | H-index |
|   |               |          | TP10 | TC10| T50  |
| 1 | Nitsche MA    | Germany  | 147  | 14538 | 66 | 105 | 5968 | 17 | 232 | 16150 | 69 |
| 2 | Paulus W      | Germany  | 130  | 13376 | 62 | 94  | 5608 | 4  | 1557 | 52383 | 106 |
| 3 | Fregni F      | USA      | 169  | 8529  | 47 | 159 | 6613 | 7  | 414  | 15365 | 62 |
| 4 | Pascual-Leone A| USA     | 71   | 6663  | 39 | 63  | 4939 | 3  | 663  | 31649 | 97 |
| 5 | Boggio PS     | Brazil   | 71   | 5281  | 33 | 63  | 3514 | 5  | 114  | 6717  | 39 |
| 6 | Antal A       | Germany  | 66   | 4910  | 34 | 51  | 2947 | 4  | 296  | 7702  | 41 |
| 7 | Cohen LG      | USA      | 31   | 4164  | 22 | 28  | 2745 | 4  | 515  | 33577 | 99 |
| 8 | Liebetanz D   | Germany  | 29   | 3411  | 23 | 16  | 1079 | 1  | 77   | 4165  | 29 |
| 9 | Tergau F      | Germany  | 16   | 3030  | 15 | 3   | 470  | 1  | 82   | 5591  | 35 |
| 10 | Priori A      | Italy    | 49   | 2725  | 25 | 48  | 2550 | 0  | 277  | 8476  | 47 |
| 11 | Rothwell JC   | England  | 30   | 2536  | 18 | 23  | 1040 | 0  | 875  | 50860 | 118 |
| 12 | Bikson M      | USA      | 65   | 2003  | 23 | 65  | 2003 | 0  | 143  | 4498  | 35 |
| 13 | Floel A       | Germany  | 33   | 1646  | 17 | 32  | 1110 | 0  | 159  | 5035  | 40 |
| 14 | Ferrucci R    | Italy    | 30   | 1541  | 19 | 29  | 1314 | 1  | 70   | 1642  | 20 |
| 15 | Brunoni AR    | Brazil   | 65   | 1366  | 20 | 65  | 1366 | 2  | 136  | 2187  | 22 |
| 16 | Datta A       | USA      | 30   | 1360  | 19 | 30  | 1360 | 1  | 3534 | 52693 | 91 |
| 17 | Kuo MF        | Germany  | 23   | 1292  | 16 | 22  | 1262 | 0  | 123  | 1938  | 24 |
| 18 | Schlau G      | USA      | 21   | 1155  | 16 | 19  | 1000 | 0  | 331  | 15282 | 70 |
| 19 | Celnik P      | USA      | 15   | 1136  | 11 | 14  | 600  | 1  | 65   | 4960  | 27 |
| 20 | Fecteau S     | USA      | 18   | 1069  | 11 | 18  | 1069 | 3  | 71   | 2638  | 26 |
| 21 | Bolognini N   | Italy    | 21   | 773   | 11 | 21  | 773  | 1  | 200  | 2730  | 25 |
| 22 | Vergani M     | Italy    | 16   | 732   | 11 | 16  | 732  | 0  | 57   | 972   | 16 |
| 23 | Loo CK        | Australia| 24   | 571   | 11 | 24  | 571  | 0  | 209  | 2445  | 26 |
| 24 | Lavido M      | Israel   | 23   | 563   | 11 | 23  | 563  | 0  | 101  | 1651  | 25 |
| 25 | Fink GR       | Germany  | 17   | 517   | 8  | 17  | 517  | 0  | 893  | 67713 | 138 |
| 26 | Minuissi C    | Italy    | 23   | 513   | 13 | 23  | 513  | 1  | 186  | 7261  | 48 |
| 27 | Byblow WD     | New Zealand| 15  | 501   | 10 | 15  | 501  | 0  | 129  | 3875  | 35 |
| 28 | Alonzo A      | Australia| 20   | 479   | 10 | 20  | 479  | 0  | 1161 | 2520  | 25 |
| 29 | Bensenor IM   | Brazil   | 29   | 450   | 13 | 29  | 450  | 0  | 215  | 2586  | 22 |
| 30 | Fitzgerald PB | Australia| 24   | 450   | 9  | 24  | 450  | 0  | 387  | 8531  | 46 |
| 31 | Padberg F     | Germany  | 23   | 417   | 8  | 23  | 417  | 0  | 334  | 10012 | 48 |
| 32 | Lang N        | Germany  | 26   | 413   | 22 | 14  | 1540 | 3  | 1666 | 59279 | 118 |
| 33 | Lotufo PA     | Brazil   | 26   | 406   | 11 | 26  | 406  | 0  | 264  | 49180 | 27 |
| 34 | Meinzer M     | Australia| 17   | 366   | 9  | 17  | 366  | 0  | 66   | 1441  | 22 |
| 35 | Palm U        | Germany  | 22   | 362   | 7  | 22  | 362  | 0  | 210  | 1297  | 19 |
| 36 | Plewnia C     | Germany  | 16   | 355   | 8  | 16  | 355  | 0  | 92   | 1614  | 22 |
| 37 | Lefaucheur JP | France   | 19   | 342   | 9  | 19  | 342  | 0  | 292  | 8581  | 47 |
| 38 | DE Ridder D   | Belgium  | 16   | 334   | 11 | 16  | 334  | 0  | 803  | 13992 | 57 |
| 39 | Cotelli M     | Italy    | 16   | 247   | 8  | 16  | 247  | 0  | 125  | 1809  | 23 |
| 40 | Jaberzadeh S  | Australia| 16   | 173   | 7  | 16  | 173  | 0  | 43   | 411   | 12 |

Results in Table 9 reveal that Gottingen University, Germany is highly influential in the tDCS research which has obtained the higher number of citations (4644 in selected journals whereas 16538 in all WOS journals). The Harvard University, USA has received the 2nd position with higher number of citations (3654 in selected journals whereas 11148 in all WOS journals) in the field of tDCS. It is worth noting that among 25 institutions, western institutions are leading in the tDCS research. Furthermore: 56.0 % institutions belong to Germany and USA only followed by 16.0 % institutions belong to Australia.
Table 7: Total papers classified by selected journals.

| Rank | Author               | BS | FHN | PO | NL | CN | JN | Total |
|------|----------------------|----|-----|----|----|----|----|-------|
| 1    | Fregni F             | 18 | 4   | 5  | 9  | 6  | 3  | 45    |
| 2    | Nitsche MA           | 16 | 3   | 1  | 2  | 6  | 8  | 36    |
| 3    | Paulus W             | 14 | 1   | 2  | 8  | 19 | 35  |
| 4    | Bikson M             | 14 | 5   | 3  | 0  | 2  | 0  | 24    |
| 5    | Boggio PS            | 5  | 2   | 4  | 1  | 1  | 19  |
| 6    | Pascual-Leone A      | 9  | 0   | 2  | 1  | 1  | 2  | 15    |
| 7    | Antal A              | 8  | 1   | 1  | 1  | 0  | 14  |
| 8    | Brunoni AR           | 5  | 0   | 3  | 2  | 0  | 13  |
| 9    | Priori A             | 6  | 1   | 1  | 2  | 0  | 12  |
| 10   | Kuo MF               | 4  | 0   | 0  | 0  | 6  | 10  |

Table 8: The most influential institutions in tDCS research.

| R    | Name                               | Country      | tDCS articles in selected six journals | tDCS articles in all WOS journals |
|------|------------------------------------|--------------|----------------------------------------|----------------------------------|
|      |                                    |              | H | TP | TC | H | TP | TC | H |
| 1    | Univ Gottingen                     | Germany      | 33 | 64 | 4644 | 183 | 16538 | 72 |
| 2    | Harvard Univ                       | USA          | 29 | 68 | 3654 | 235 | 11148 | 56 |
| 3    | Ninds                              | USA          | 12 | 13 | 2417 | 38  | 4674  | 24 |
| 4    | Beth Israel Deaconess MED CTR      | USA          | 11 | 17 | 2004 | 48  | 3221  | 25 |
| 5    | Univ Kiel                          | Germany      | 6  | 8  | 1547 | 25  | 2590  | 18 |
| 6    | Univ Milan                         | Italy        | 9  | 13 | 1389 | 55  | 2942  | 26 |
| 7    | UCL                                | Germany      | 15 | 25 | 1337 | 77  | 2742  | 25 |
| 8    | Univ Prebiteriana Mackenzie        | Brazil       | 12 | 19 | 1268 | 58  | 2830  | 27 |
| 9    | Cuny City Coll                     | USA          | 16 | 31 | 1222 | 60  | 1914  | 23 |
| 10   | Univ Sao Paulo                     | Brazil       | 11 | 22 | 923  | 103 | 4198  | 29 |
| 11   | Univ Tubingen                      | Germany      | 7  | 17 | 853  | 38  | 1687  | 13 |
| 12   | Univ Oxford                        | England      | 10 | 15 | 570  | 41  | 1500  | 17 |
| 13   | Johns Hopkins Univ                 | USA          | 7  | 9  | 466  | 30  | 1535  | 17 |
| 14   | Univ Munich                        | Germany      | 7  | 10 | 405  | 29  | 500   | 10 |
| 15   | Spaulding Rehabil                  | USA          | 8  | 9  | 397  | 20  | 536   | 11 |
| 16   | Charite                            | Germany      | 10 | 17 | 373  | 45  | 842   | 14 |
| 17   | Univ Penn                          | USA          | 10 | 20 | 336  | 35  | 670   | 17 |
| 18   | Univ Auckland                      | New Zealand  | 5  | 6  | 333  | 28  | 602   | 13 |
| 19   | Monash Univ                        | Australia    | 8  | 17 | 315  | 36  | 489   | 10 |
| 20   | Univ Brescia                       | Italy        | 8  | 13 | 285  | 29  | 526   | 13 |
| 21   | Univ New S Wales                   | Australia    | 7  | 11 | 126  | 38  | 696   | 14 |
| 22   | Max Planck Inst Human Cognit Brain | Germany      | 6  | 9  | 106  | 21  | 209   | 9  |
| 23   | Univ Queensland                    | Australia    | 5  | 11 | 100  | 29  | 313   | 10 |
| 24   | ST George HOSP                     | Australia    | 6  | 6  | 98   | 23  | 535   | 11 |
| 25   | Bar Ilan Univ                      | Israel       | 3  | 5  | 93   | 26  | 518   | 10 |

In general; out of twenty-five selected institutions; 18 institutions are Germany, American and Australian based institutions. Asian institutions are totally absent in the top 25 list.

**Most influential countries in tDCS research**

Figure 7 showed an interesting bibliometric indicator is to classify the authors and institutions by countries.

Thus, we can see the regions where tDCS research is more active and influential. For doing this, Table 9 presents the 30 most productive countries in the tDCS.
### Table 9: The most influential countries in TDCS research.

| Rank | Name          | TP  | TC  | >500 | >100 | >50  | TP10 | TC10 | H   |
|------|---------------|-----|-----|------|------|------|------|------|-----|
| 1    | Germany       | 492 | 25137 | 5   | 60  | 61   | 440  | 14012 | 84  |
| 2    | USA           | 651 | 20535 | 3   | 40  | 64   | 634  | 16698 | 70  |
| 3    | Italy         | 278 | 7271  | 1   | 14  | 20   | 273  | 6356  | 42  |
| 4    | Brazil        | 201 | 7043  | 1   | 17  | 16   | 191  | 5117  | 39  |
| 5    | England       | 226 | 6820  | 0   | 19  | 19   | 218  | 5254  | 42  |
| 6    | Australia     | 185 | 2753  | 0   | 2   | 12   | 185  | 2753  | 28  |
| 7    | Spain         | 61  | 2441  | 0   | 7   | 5    | 60   | 2160  | 26  |
| 8    | France        | 75  | 1478  | 0   | 4   | 4    | 75   | 1478  | 20  |
| 9    | South Korea   | 68  | 1191  | 0   | 1   | 6    | 68   | 1191  | 19  |
| 10   | Canada        | 87  | 1163  | 0   | 2   | 4    | 5117 | 1142  | 18  |
| 11   | Switzerland   | 48  | 981   | 0   | 2   | 5    | 47   | 917   | 16  |
| 12   | Japan         | 76  | 946   | 0   | 1   | 5    | 75   | 854   | 17  |
| 13   | Hungary       | 15  | 667   | 0   | 2   | 3    | 13   | 475   | 11  |
| 14   | New Zealand   | 37  | 660   | 0   | 1   | 2    | 37   | 660   | 14  |
| 15   | Israel        | 33  | 600   | 0   | 1   | 3    | 33   | 600   | 11  |
| 16   | Portugal      | 18  | 600   | 0   | 1   | 3    | 17   | 301   | 9   |
| 17   | Netherlands   | 62  | 443   | 0   | 1   | 6    | 62   | 443   | 11  |
| 18   | Denmark       | 15  | 350   | 0   | 0   | 1    | 15   | 350   | 10  |
| 19   | Taiwan        | 22  | 296   | 0   | 0   | 2    | 22   | 296   | 8   |
| 20   | China         | 47  | 272   | 0   | 0   | 2    | 47   | 272   | 9   |
| 21   | Austria       | 20  | 230   | 0   | 0   | 2    | 20   | 230   | 7   |
| 22   | Russia        | 8   | 119   | 0   | 0   | 1    | 7    | 116   | 4   |
| 23   | Belgium       | 81  | 114   | 0   | 0   | 5    | 81   | 114   | 20  |
| 24   | Poland        | 13  | 92    | 0   | 0   | 0    | 13   | 92    | 6   |
| 25   | Iran          | 14  | 80    | 0   | 0   | 0    | 14   | 80    | 4   |
| 26   | Thailand      | 9   | 80    | 0   | 0   | 0    | 9    | 80    | 3   |
| 27   | Turkey        | 10  | 76    | 0   | 0   | 1    | 10   | 76    | 3   |
| 28   | India         | 15  | 69    | 0   | 0   | 0    | 15   | 69    | 5   |
| 29   | Ireland       | 8   | 63    | 0   | 0   | 0    | 8    | 63    | 5   |
| 30   | Wales         | 9   | 38    | 0   | 0   | 0    | 9    | 38    | 3   |

**Figure 6:** Authors published papers in transcranial direct current stimulation (tDCS) field and co-occurrence with key words of tDCS.

**Figure 7:** Citation graph between authors papers in transcranial direct current stimulation field.
The countries are ranked by total number of citations received as well as by their research productivity; although some other bibliometric indicators are also considered including the total number of citations, H-index, the number of articles and citations received in last 10 (TP10 and TC10) as well as the number of articles which have received more than >500, >100 and >50 citations. Germany, USA and Italy are the leading countries in tDCS research. Note that England, Brazil, Australia and Canada are also obtaining promising results in regards to total number of citations. It is also noted that some Asian countries are also starting appearing in the selected list in recent years as well.

**Bibliometric coupling and graphical analysis**

The graphical representation of the tDCS research articles is conducted in this section. Figure 8 showed the graphs are giving a visualized picture of the common work and occurrence of authors, organizations, and documents. For doing so, we use the VOS viewer software that visualizes the bibliographic material through co-authorship, co-occurrence, citation, bibliographic coupling and co-citation analysis. Note that the graph visualizes those variables mostly meet the bibliographic parameters. In the bibliometric coupling graphs, circles are representing the set (authors, organizations, etc.), so the bigger the circle means that this corresponding set has a more link strength. Link strength represents the number of times a corresponding set has been repeated in the relevant field (co-authorship, co-occurrence, etc.). The lines between the authors, organizations, and so on, represent repetitions; thus, the thickest line provides the strongest relation.43

**Co-authorship analysis**

Co-authorship illustrates the volume of publications by authors, organizations, and countries and shows how they are connected. First, Co-authorship shows the volume of publications of a set of variables (authors, organizations, and countries) and how they are connected between them. Regarding the co-authorship between authors in tDCS, Figure 4 reveals that Fregni F has the greatest co-authorship among all other authors. Fregni F exits 539 times (total link strength according to VOS Viewer analysis) with other authors in all his 169 published articles, for example he published 54 articles with Pogo PS.

Note that the total link strength is represent the relation of co-authorship of a set with all other, and it doesn't equal to the number of publications, because the set may have more than one co-authorship in the same paper and then will be counted more than one. Then, Nitsche MA comes in the second position having greatest co-authorship with 479 total link strength, and the most partner for Nitsche MA is Paulus W who is also having the third strongest link strength. Nitsche and Paulus published 86 papers together in the tDCS field. Furthermore, most of the papers by Nitsche and Paulus are published early in 2008, whereas most of papers published by Fregni are around 2014 as shown below in the color key in the right down of the figure. It is worth noting that all top authors in TDCS are mostly publishing as two more authors.

**Co-authorship organizational analysis**

Furthermore, inter-organization co-authorship is shown in Figure 5. Among all organizations publishing in tDCS, Harvard University has the strongest co-authorship with other organizations. It has 578 co-authorships with all other organizations, and the most partner was Sao Paulo University, which is also comes second with 321 total link strength.

**Co-occurrence analysis**

Co-occurrence measures the number of times that a keyword appears in the documents considered. Figure 4 presents the keywords mostly used in the tDCS field. Author keywords (the keywords that appear in the first page of many journals) are considered to visualize the existing of our related keywords and their common existing in the same paper.

Figure 6 shows that keyword “Transcranial direct current stimulation” and its abbreviation used in this research study are the strongest occurrence (existence in papers considered) and have the strongest link (common existing with other keywords), which are placed in the core of the graph. Transcranial direct current stimulation has 1707 common occurrences with other keywords, and the keyword “Transcranial magnetic stimulation” has the most common occurrence with it, which also comes in the third position. "Brain stimulation" also comes fourth with 1322 link strength.

**Citation coupling analysis**

Citation between authors measures the direct citations between two authors in the set considered (documents, sources, authors, organizations, or countries). For example, with two authors, the connection represents the number of times author X has cited Y plus the number of times that author Y has cited X inside the set of documents considered. Note that here one visualizes the two documents that gives the citation but not the third document that receives the other two citations. Citations between authors are shown in Figure 7 which depict that Nitsche MA is the most authors received and cited others in his 148 papers appeared in this part of analysis. Nitsche received the most citations from Fregni F which is also comes in the third position after Paulus.

**Bibliographic coupling analysis**

The connections show the variables (documents, sources, authors, organizations, or countries) that cite the same documents. But not necessarily they are co-authors. Note
that the two connected documents appear in the figure but not the third one unless it also has a significant degree of bibliographic coupling through other documents. Figure 8 illustrates the bibliographic coupling between authors. The results again show that Nitsche MA has the most common reference with other authors having 1272472 link strength.

![Figure 8: Bibliographic coupling of authors that publish papers in transcranial direct current stimulation field.](image)

Note that link strength here means the times author number 1 and another author number 2 have cited a third author at the same time, and these number will be counted more than one in the same paper if it is repeated with other authors. For example, Nitsche MA has cited the same authors with Paulus W 79690 times, who come in the third position after Fregni.

CONCLUSION

This study has presented a quantitative analysis and visualization of bibliometric indicators in the field of tDCS research. Initially, analyzing the WOS data; results reveal that since 2011 there is a growing interest by researchers in the field. BI indicators such as total number of publications and citations are increasing exponentially with positive trend. Results also reveal that country wise, Germany is the most influential country with higher number of citations; whereas United States is the most productive country with higher number of publications. It is also observed that some developing countries are also appearing in the list including Brazil, South Korea, India, Iran, Thailand and Turkey. Currently, they do not have significant position; however, it is expected that their contributions will continue to grow significantly in future. Nitsche Ma and Paulus W from Germany appeared as the most active and influential authors followed by Fregni F from USA. Among institutions; University of Gottingen (Germany) holds the most influential institution position, however Harvard University is the most productive institutions in tDCS research. Australia has many influential institutions and researchers, since there are four Australian institutions in the twenty-five most influential institution list, and the same thing occurred in the list of the most influential authors. Among 25 top institutions, western institutions are leading in the tDCS research. 56.0 % institutions belong to Germany and USA only followed by 16.0 % institutions belongs to Australia. Asian institutions are totally absent among the selected twenty-five most influential institution list. Study also reveals that Brain Stimulation journal is the top most productive and influential journal; which publishes 17 % tDCS research papers followed by Frontiers in Human Neuroscience (1.96%) and Neuro-rehabilitation and Neural Repair (1.75%) respectively.

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