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Dominio del conocimiento y tendencias emergentes en estimulación cerebral no invasiva: un análisis bibliométrico a través de CiteSpace

Knowledge domain and emerging trends in non-invasive brain stimulation: a bibliometric analysis via CiteSpace

Tendencias emergentes en estimulación cerebral no invasiva

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Desirée Victoria-Montesinos: concepción del estudio.

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Introducción. En las últimas décadas se han desarrollado nuevas técnicas y protocolos de estimulación cerebral no invasiva (NIBS), como la estimulación magnética transcraneal (EMT) y la estimulación transcraneal con corriente directa (tDCS).

Objetivo. Identificar y visualizar la estructura intelectual de la estimulación cerebral no invasiva a través del análisis de co-citación de documentos.

Materiales y métodos. En este estudio se analizaron 30.854 manuscritos indexados en Web of Science sobre estimulación cerebral no invasiva, todos ellos publicados entre 1988 y 2022, y sus 1.615.692 referencias. Se dibujó un mapa de red de co-citación de documentos utilizando el software CiteSpace.

Resultados. La revista más productiva fue Clinical Neurophysiology. La institución y país más productivos son University College London y USA. El autor más productivo fue Álvaro Pascual-Leone y el autor más co-citado en el campo de los NIBS es Rothwell JC. Además, el estudio más citado fue Rossi et al. (2009). La aplicación segura de los NIBS y sus efectos sobre la función motora o las funciones ejecutivas son una tendencia emergente en la investigación sobre los NIBS.

Conclusiones. La presente investigación muestra un enfoque cienciométrico cuantitativo y profundiza en el avance de la investigación sobre estimulación cerebral no invasiva mediante el examen de las referencias publicadas en este ámbito. Estos resultados pueden ser de gran utilidad para los profesionales que deseen hacerse una idea de los patrones de reconocimiento y las nuevas orientaciones en este campo.

Keywords: estimulación magnética transcraneal; bibliometría.

Introduction. In recent decades, new non-invasive brain stimulation (NIBS) techniques and protocols have been developed, as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS).

Objective. To identify and visualize the intellectual structure of noninvasive brain stimulation through document co-citation analysis.

Material and methods. In this study, 30854 Web of Science indexed manuscripts regarding non-invasive brain stimulation, all published from 1988 to 2022, and their 1,615,692 references were analyzed. A document co-citation network map was drawn using CiteSpace software.

Results. The most productive journal was Clinical Neurophysiology. The most productive institution and country are University College London and USA. The most productive author was Alvaro Pascual-Leone and the most cited author in the field of NIBS was Rothwell JC. In addition, the most cited study was that of Rossi et al. (2009). The safe application of NIBS and its effects on motor function or executive functions are an emerging trend in NIBS research.

Conclusions. The current investigation showcased a quantitative scientometric approach and delved into the advancement of NIBS research by examining the references published in this domain. These finding can be valuable for professionals looking to gain a visual grasp of the patterns of recognition and emerging directions in the field.

Keywords: transcranial magnetic stimulation; bibliometrics;

Non-invasive brain stimulation (NIBS) has attracted the interest of the general public and researchers since Anthony Barker first described transcranial magnetic stimulation at the University of Sheffield (UK) in 1985 and consequently, there has been an increasing number of scientific publications in this field (1–3). In recent decades, new NIBS techniques and protocols have been developed, including transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) (4,5).

For the development of these techniques, as in other scientific areas, researchers are obliged to consult large amounts of scientific literature to develop their work, which involves a high time expenditure and a huge complexity (6,7). Thus, as we move towards an information and knowledge society, it is necessary to have quantitative indicators and tools that make it possible to objectify the differences between the publications (6,8).

For several decades, methodological models have been developed that allow us to understand the development of scientific activity. Bibliometric studies offer a statistical and quantitative analysis of published articles, and provide insight into their impact on a field of research (9–13).

The first works on Bibliometrics were carried out by Garfield, Kessler and Price (14–16), who observed that in the statistical analysis of bibliographic references and citations, patterns that establish thematic associations between scientific works could be found (9,14–18). Years later, Small and Marshakova (19,20) proposed co-citation analysis as an objective model to reveal the intellectual structure of scientific specialties (9,19,20).

Co-citation analysis is based on the hypothesis that there is a thematic similarity between two or more documents that are cited in the same document, and the higher frequency of co-citation, the greater affinity between them (9). If a co-citation analysis is performed correctly, it will be possible to know the most relevant authors or papers in a discipline through the empirical consensus established by the hundreds of citators of those authors or papers, and not only by the impressions of a single researcher (6,17,21).

If it is accepted that the most cited papers represent the key concepts, methods or experiments in a field, co-citation patterns can be used as a technique to contribute to the knowledge of the intellectual structure of scientific disciplines (9,22). So that bibliometric studies are applicable to areas such as neurology, where similar analyses have been performed for other neuropsychiatric treatments (23-26).

On the other hand, CiteSpace is a freely available Java softwave invented in early 2004 by Professor Chaomei Chen to perform bibliometric analysis. It is characterized by analyzing and visualizing network maps of authors, keywords, institutions, countries, subject categories, and co-citation networks of cited authors, cited references and cited journals (11,27-33).

The graphs obtained from CiteSpace are composed of two main elements, the nodes and the links (6,11,31). Each node represents elements such as a citation, institution, author and country, and each link between two nodes involves a cocitation relationship between them. Thus, the size of the nodes represents the individual citation frequency of each document and the thickness of the links represents the cocitation strength between 2 nodes. Additionally, the grey tone of the nodes and lines represents different years (6,11,31).

After what was exposed, the main objective of this study is to identify and visualize the intellectual structure of noninvasive brain stimulation through document cocitation analysis.

Material and methods

The data utilized for bibliometric analysis was sourced from the Web of Science Core Collection by Clarivate Analytics (26). The index term included “non-invasive brain stimulation" OR "non-invasive electrical brain stimulation" OR "non-invasive magnetic brain stimulation" OR "transcranial direct current stimulation" OR "transcranial magnetic stimulation". As a result, a total of 30,854 studies were identified, encompassing 25,993 research originals and reviews, with a cumulative count of 1,615,692 references. These search records were subsequently exported to CiteSpace for further analysis. Studies were download on March 24, 2022. Each download study included full records and cited references. Inclusion criteria were original articles and reviews on non-invasive brain stimulation retrieved from the Web of Science published from 1985 to 2022. No exclusion criteria were described.

CiteSpace is a Java-based software utilized for the visualization of scientific bibliometric analysis (28). In this study, CiteSpace (6.1.R1) was employed to perform a scientometric analysis. The chosen timeframe extended from January 1988 to December 2022, utilizing a time slice of 5 years, selection criteria were top 50 (items more cited) per slice and the rest of the settings as default (26,27).

We observed the number of publications on NIBS in each year studied and performed an analysis of the most productive journals and authors as well as the most co-cited authors, institutions, countries and documents. Finally, three labeling algorithms were used to find out the topics analyzed in the studies of each cluster: Latent Semantic Indexing (LSI), Log-likelihood ratio (LLR) and mutual information (MI) and we analyzed the burst citations to identify emerging trends (26,27).

The indicators used were the number of citations received, centrality and the strongest citation bursts. The network maps obtained from the Citespace software are made up of nodes and links. The size of the nodes represents the number of citations received by an item and the thickness of the links and the short distance between two nodes represents the co-occurrence strength between two items.

This bibliometric study uses secondary databases in the public domain and therefore does not require the approval of an institutional ethics committee.

Results

Publication years and journals

As shown in figure 1, the total number of publications increased since 1988 to 2022. The examined timeframe can be categorized into three distinct stages: the initial stage spanning from 1988 to 1995, the second stage encompassing the years from 1996 to 2010, and the third stage extending from 2011 to 2022. The first period is characterized by the rapid growth in the number of publications, this number grew from 3 publications in 1988 to 94 publications in 1995. The period from 1996 to 2010 had a progressive development, while the third period shows an explosive growth because the total number of publications (18,636) is higher than in the two previous periods combined (7357).

The top ten journals with the highest volume of published research on NIBS are presented in table 1, serving as a valuable point of reference for new researchers. NIBS articles are distributed in a total of 2310 journals. The most productive journal is *Clinical Neurophysiology* (928 articles). The second-ranked journal was *Brain Stimulation* (854 articles).

Author and co-authorship

Knowledge maps can offer insights into prominent authors and assist researchers in forging collaborative connections. Table 2 shows the top 10 authors who have published articles related to NIBS. The most productive author is Álvaro Pascual-Leone.

The co-authorship network is displayed in figure 2, and contains 248 unique nodes and 558 links. The number of cites recibed by the author is represented in the size of the circle and the thickness of the links represents the cocitation strength between two authors. The color of the nodes represents different years. In **Figure 2** we observe that the most representative author in the field of NIBS is Rothwell JC with a total of 390 cites, followed by Álvaro Pascual-Leone (352) and Felipe Fregni (337).

Co-institute and Co-country

Table 3 shows the top 10 institute and countries who have published articles related to NIBS. We can highlight that the most productive institutions have been the University of London (1434 publications) and Harvard University (1423 publications), while the countries with the most publications on NIBS are the United States of America (7497) and Germany (4012).

Figure 3 display co-insititute results in the field of NIBS. The number of cites recibed by the insitute is represented in the size of the circle. The thickness of the links and the short distance between two circles represents the co-ocurrence strength between two institutes. The institution with the highest citation frequency is University College London in the UK with a total of 764 cites, followed by Harvard University (720) and University of Toronto (695). External black rings indicate that these institutes have greater centrality. The institutions with the highest centrality were National Institute of Neurological Disorders Stroke NINDS (0.21) in France followed by University of Sidney and University College London with 0.18 and 0.17 respectively. Figure 4 exhibits co-country results in the field of NIBS. The countries that received the most citations are USA (7428), Germany (3946) and Italy (3410). In addition, we can observe that the countries with the highest centrality were USA (0.40), England (0.33) and Germany (0.26).

Document co-citation analysis

25,993 studies were analyzed using CiteSpace software. A map of the document co-citation network is shown in figure 5, and contains 299 nodes and 307 lines. These nodes and lines represent the number of citations each study has received and the relationship of co-citations of the studies collected, respectively. The node size increases with higher citation counts for the study, while the color and thickness of the circle within the node reflect the citation frequency across various time periods. Internal rings represent earlier cited studies, while external rings represent more recently cited studies. The width of an annual ring corresponds to the quantity of citations within a specific time period.

The most cited papers are Rossi et al. (34) in cluster 11 with a total of 1082 citations, followed by Rossini et al. (35) in cluster 11 with 610 citations, Huang et al. (36) in cluster 6 with 537 citations, and Nitsche et al. (37) in cluster 10 with 527 citations.

The co-citation analysis of NIBS papers generated 17 co-citation clusters, each labeled with indexed terms derived from their own citations. To find out the topics analyzed in the studies of each cluster, CiteSpace can extract noun phrases from article titles for clustering based on three labeling algorithms: Latent Semantic Indexing (LSI), Log-likelihood ratio (LLR), and mutual information (MI). The log-likelihood ratio typically yields superior outcomes in terms of the distinctiveness and scope of topics linked to clustering (27). Table 4 presents an overview of the 17 clusters, each with a contour value exceeding 0.8, signifying dependable and significant results.

Emerging trends

Articles exhibiting bursts of citations indicate a notable surge in research interest within the NIBS field. Table 5 enumerates the top 10 references displaying the most pronounced citation bursts from 1988 to 2022. The initial three references underscore the emerging trend of NIBS research from 1998 to 2007, while the middle three highlight the emerging trend of new research from 2005 to 2017. The last four references were those that received significant attention from 2013 to 2022, and which is the focus of current NIBS research. Ziemann et al. (38) reported that TMS can be used as an assessment tool to measure the effects of antiepileptic drugs. Chen et al. (39) hypothesized that the reduction of cortical excitability induced by TMS has potential clinical applications in diseases such as epilepsy and myoclonus. Huang et al. (36) described an rTMS method that allowed long-lasting effects on human motor cortex as conventional TMS applications had weak effects on neuronal plasticity. Stagg et al. (40) summarized the physiological effects of tDCS and introduced the theoretical framework of how tDCS influences motor learning. On the other hand, it should be noted that 6 of the 10 articles with the strongest citation bursts focused their research on establishing guidelines for the safe and effective application of NIBS. Initially, Wassermann et al. (41) proposed guidelines stemming from the International Workshop on the Safety of Repetitive Transcranial Magnetic Stimulation. Rossi et al. (34) updated the guidelines for safety application of TMS based on an expert consensus that took place at the conference in Siena (Italy). Nitsche et al. (37) and Rossini et al. (35) provided information to perform safe and effective application of tDCS, furthermore, Rossini et al. (35) updated the guidelines for application of tDCS and TMS in both brain and spinal cord and peripheral nerves. Finally, Lefaucheur et al. (42) and Lefaucheur et al. (43) summarized the conclusions of the European expert group on the application of rTMS and tDCS respectively on pain and depression. We should highlight that Lefaucheur et al. (43) showed their concern about an inappropriate use of tDCS, since the low cost and easy application mean that this treatment can be performed by the patient at home, with the danger that excessive applications may be performed that produce adverse effects on the patient.

References with elevated burst values are presented in table 5. The study with the highest ranking was conducted by Rossi et al. (34) within Cluster 11, boasting a burst value of 388.36. Following closely, the second-highest ranked study was authored by Rossini et al. (35) in Cluster 11, holding a burst value of 245.37. The third-ranked study, belonging to Huang et al. (36), was situated in Cluster 6 and featured a burst value of 201.31. These studies are important because they described safe application guidelines for both TMS and tDCS and developed new application methods for a longer lasting effect.

Discussion

These results indicate that NIBS as a treatment and diagnostic tool is receiving increased attention and that more research is being performed on non-invasive brain stimulation. This exponential growth is in line with the general scope as shown by a search performed in Pubmed with MeSH terms in the area of neurology where a growth of similar characteristics and form is observed in the period studied. Clinical Neurophysiology is a professional journal dedicated to publishing about pathophysiology underlying diseases of the peripheral and central nervous system of humans. The journal has been included in the Web of Science since 1999 and has accumulated a total of 7,994 publications, with 25,162 citations in the year 2021. Brain Stimulation specializes in the publication of research on neuromodulation and centers its scope on the domain of brain stimulation, encompassing both invasive and non-invasive methodologies and technologies that modify brain function via electrical, magnetic, radiowave, or precisely targeted pharmacological stimulation. The journal has been indexed in the Web of Science since 2008 and has amassed a total of 2,258 publications, which received 10,760 citations in the year 2021. This analysis provides highly personalized information for other researchers. Álvaro Pascual-Leone is a Spanish neurologist and professor at Harvard University (USA) who studies brain plasticity and the development of transcranial magnetic stimulation in the field of cognitive neuroscience and neurorehabilitation. One of his most cited studies deals with the benefits of Rapid-rate transcranial magnetic stimulation (rTMS) in depression (44).

Rothwell JC investigated the modulation of motor cortex excitability and electromyographic responses of limb muscles during electrical stimulation of the motor cortex (45,46).

The presence of two authors from different institutions within the same article signifies a collaborative effort, and the CiteSpace software facilitates the analysis of such collaborations through a co-occurrence frequency map. Analyses of cooperations in institutions and countries could help to develop teamwork and global cooperation in NIBS. It is also useful for researchers to make the best use of available resources to increase efficiency.

The CiteSpace software provides a map of the document co-citation network with nodes and lines representing the number of citations each study has received and the ratio of co-citations of the collected studies, respectively. The most representative study was that of Rossi et al. (47), this study has noted a remarkable increase in the utilization of conventional TMS applications over the past few decades, new types of TMS such as repetitive TMS have been developed and advancements in technology have resulted in the development of novel device designs and the incorporation of TMS with electroencephalography (EEG), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI). This made it possible to evaluate the adverse effects more related to TMS such as the occurrence of seizures in a larger number of subjects. All this resulted in the updating of the ethical considerations and guidelines for safe application of TMS based on an expert consensus that took place at the conference in Certosa di Pontignano, Siena (Italy). 6 years later Rossini et al. (35) found recent guidelines in the literature on specific aspects of noninvasive brain stimulation, such as safety

(34), methodology (47) and therapeutic applications (42). This enabled them to conduct a comprehensive and up-to-date review of the theoretical, physiological, and practical facets of non-invasive electrical and magnetic stimulation in the brain, spinal cord, nerve roots, and peripheral nerves. Huang et al. (36) observed that it had been 30 years since the effect of electrical stimulation on processes such as learning and memory had been discovered, but these effects were weak in humans and did not last longer than 30 minutes. Thus Huang et al. (36) described an rTMS method that achieved long-lasting effects on the motor cortex. Nitsche et al. (37) considered that tDCS had been introduced as a promising tool to modulate cortical function by stimulation with weak direct currents, but that application protocols needed to be established to improve the comparability of research results from different laboratories. Because of this, Nitsche et al. (37) proposed guidelines for applying tDCS safely and effectively. However, they were aware that tDCS was a young technique and that future research would make it necessary to update these guidelines.

According to the document co-citation cluster labels, it becomes apparent that experts employ non-invasive brain stimulation for both therapeutic purposes and as a diagnostic tool. Therapeutic applications focus on the stimulation of brain areas such as the motor cortex or the prefrontal area to recover motor function or executive functions such as memory respectively. These applications are used in the treatment of neurological pathologies such as stroke and psychiatric disorders such as depression. However, non-invasive brain stimulation has also been used as a diagnostic tool through the analysis of evoked potentials that allow measuring cortical excitability.

Research articles that experience citation bursts indicate a notable surge in research attention within the NIBS field. The magnitude of the burst value attributed to citations serves as a metric for gauging the novelty of the research outcomes. A citation burst is indicative of a specific publication being linked to a sudden surge in citations. Additionally, when a cluster encompasses multiple nodes with robust citation bursts, it signifies that the entire cluster represents an active area of research or an emerging trend (27).

The limitations of the study are attributed to the characteristics of CiteSpace, which only analyzes a single database and does not normalize citation data, which could result in the fusion of duplicate documents. For future research, it will be crucial to examine different databases and conduct a detailed analysis of the two main techniques: tDCS and TMS.

In conclusion, drawing from the findings in CiteSpace, we deliberated on key clustering, the established research framework, and emerging trends in the references. In exploring these results, we identified that the main domains of knowledge in NIBS research are treatments to recover neurological pathologies and psychiatric disorders. From the detected bursts of citations it could be concluded that the safe application of NIBS and its effects on motor function or executive functions are an emerging trend in NIBS research research in line with the growing trend in the area of neurology. The current research employed a quantitative scientometric approach to examine the advancement of NIBS research through the analysis of published references in this domain. The outcomes will serve as a valuable resource for practitioners, enabling them to gain visual insights into the patterns of recognition and emerging trends.

Conflict of interest

The authors report there are no competing interests to declare.

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Table 1. Top 10 most productive journals

Journals	Number of published papers	Impact factor
Clinical Neurophysiology	928	4,861
Brain Stimulation	854	9,184
Experimental Brain Research	745	2,064
Frontiers in Human Neuroscience	567	3,473
Neuroimage	510	7,4
Plos One	488	3,752
Neuroscience Letters	450	3,197
Journal of Neurophysiology	435	2,974
Journal of Neuroscience	426	6,709
Neuropsychologia	402	3,054

Table 2. Top 10 active author

Author	**Number of published papers**
Pascual-leone A	478
Rothwell JC	390
Fregni F	375
Daskalakis ZJ	304
Fitzgerald PB	288
Paulus W	283
Nitsche MA	278
Hallett M	248
Ziemann U	239
Cohen LG	219

Table 3. Top 10 active institution and countries in NIBS

Institution			Countries		
Ranking	**Institution**	**Number of published papers**	**Ranking**	**Country**	**Number of published papers**
1	University of London	1434	1	USA	7497
2	Harvard University	1423	2	Germany	4012
3	University College London	1157	3	Italy	3424
4	University of Toronto	801	4	England	3004
5	National Institutes of Health NIH USA	775	5	Canada	2242
6	Beth Israel Deaconess Medical Center	738	6	Australia	2104
7	University of California System	702	7	China	1565
8	Institut National de la Sante ET de la Recherche Medicale INSERM	632	8	Japan	1546
9	NIH National Institute of Neurological Disorders Stroke NINDS	561	9	France	1404
10	Centre National DE LA Recherche Scientifique CNRS	526	10	Netherlands	984

NIBS: Non-invasive brain stimulation

Table 4. The 17 clusters of NIBS document co-citation, identified by subject headings

Cluster ID	Size	Silhouette	Mean(cite Year)	Label (LSI)	Label (LLR)	Label (MI)
0	22	0.908	1994	motor cortex	single motor unit	cervical nerve root compression
1	21	0.966	2018	cortical excitability	motor learning	cervical nerve root compression
2	20	0.887	2003	human motor cortex	human motor cortex	cervical nerve root compression
3	19	0.986	1997	silent period	silent period	rapid finger movement
4	18	0.916	2005	major depression	electroconvulsive therapy	cervical nerve root compression
5	18	1	2018	treatment-resistant depression	treatment-resistant depression	cervical nerve root compression
6	18	1	2009	human motor cortex	human motor cortex	cervical nerve root compression
7	17	0.974	2019	working memory	prefrontal tdc	cervical nerve root compression
8	16	0.9	1992	motor evoked-potential	motor evoked-potential	human motor cortex
9	16	0.891	2002	human motor cortex	intracortical inhibition	cervical nerve root compression
10	15	0.982	2012	psychiatric disorder	current density	cervical nerve root compression
11	15	0.91	2018	cortical excitability	human motor cortex	cervical nerve root compression
12	13	0.977	2010	chronic stroke	stroke rehabilitation	cervical nerve root compression
13	12	0.95	1992	motor evoked-potential	motor evoked-potential	human motor cortex
14	11	0.991	1995	motor cortex	hand muscle	cervical nerve root compression
15	9	1	1992	human motor cortex	intraoperative study	human motor cortex
16	8	0.938	2001	therapeutic application	therapeutic application	therapeutic application

NIBS: Non-invasive brain stimulation; LSI: Latent semantic indexing; LLR: Log-likelihood ratio; MI: mutual information

Table 5. Top 10 references with the strongest citation bursts

References	Year	Strength	Begin	End	1988 - 2022	Burst	ClusterID
Ziemann U, ANN NEUROL (Ziemann et al. 1996)	1996	128.51	1998	2007		128,51	9
Chen R, NEUROLOGY (Chen et al. 1997)	1997	145.67	1998	2007		145,67	2
Wassermann E, EVOKED POTENTIAL (Wassermann et al. 1998)	1998	186.22	1998	2007		186,22	2
Huang Y, NEURON (Huang et al. 2005)	2005	201.31	2005	2017		201,31	6
Nitsche M, BRAIN STIMUL (Nitsche et al. 2008)	2008	191.96	2008	2017		191,96	10
Rossi S, CLIN NEUROPHYSIOL (Rossi et al. 2009)	2009	388.36	2009	2017		388,36	11
Stagg C, NEUROSCIENTIST (Stagg et al. 2011)	2011	141.33	2013	2022		141,33	1
Lefaucheur J, CLIN NEUROPHYSIOL (Lefaucheur et al. 2014)	2014	187.99	2014	2022		187,99	11
Rossini P, CLIN NEUROPHYSIOL (Rossini et al. 2015)	2015	245.37	2015	2022		245,37	11
Lefaucheur J, CLIN NEUROPHYSIOL (Lefaucheur et al. 2017)	2017	147.99	2018	2022		147,99	11

Figure 1. Number of papers on non-invasive brain stimulation published from 1988 to 2022.

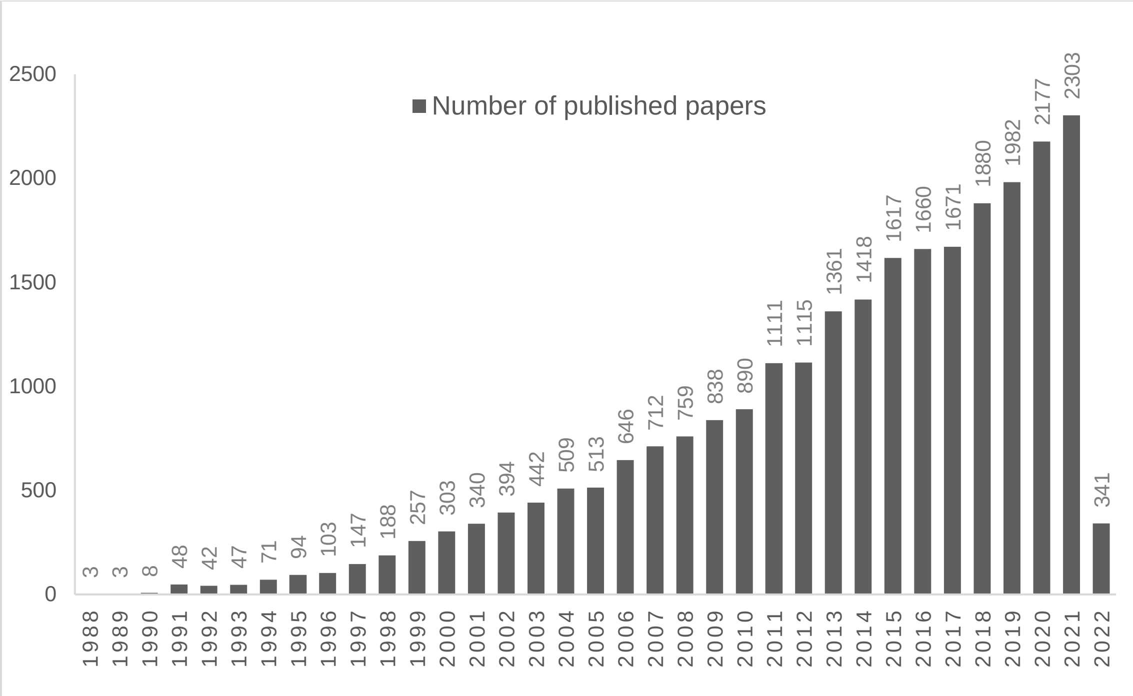
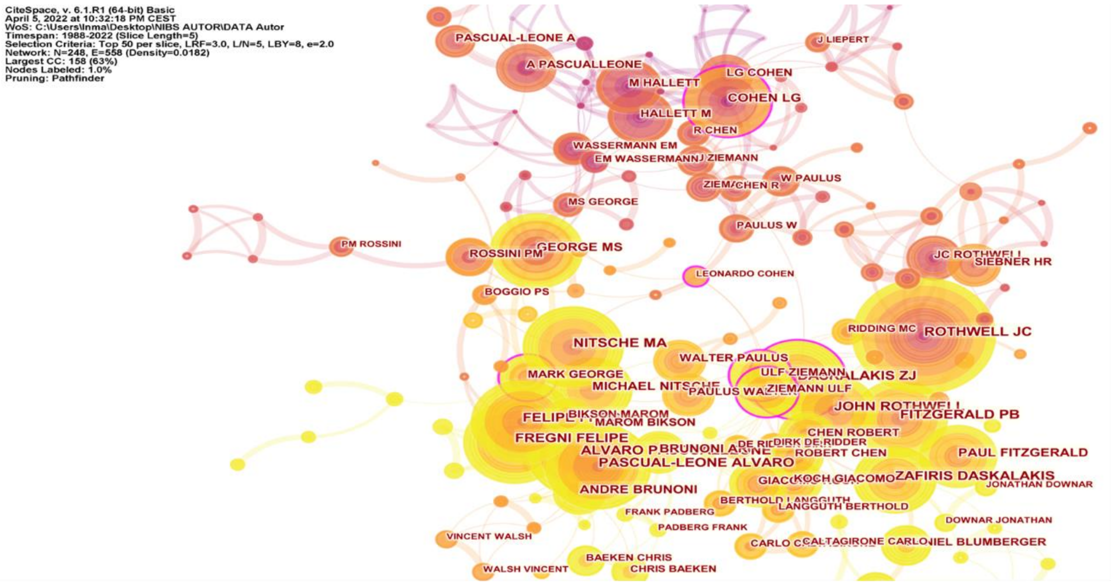
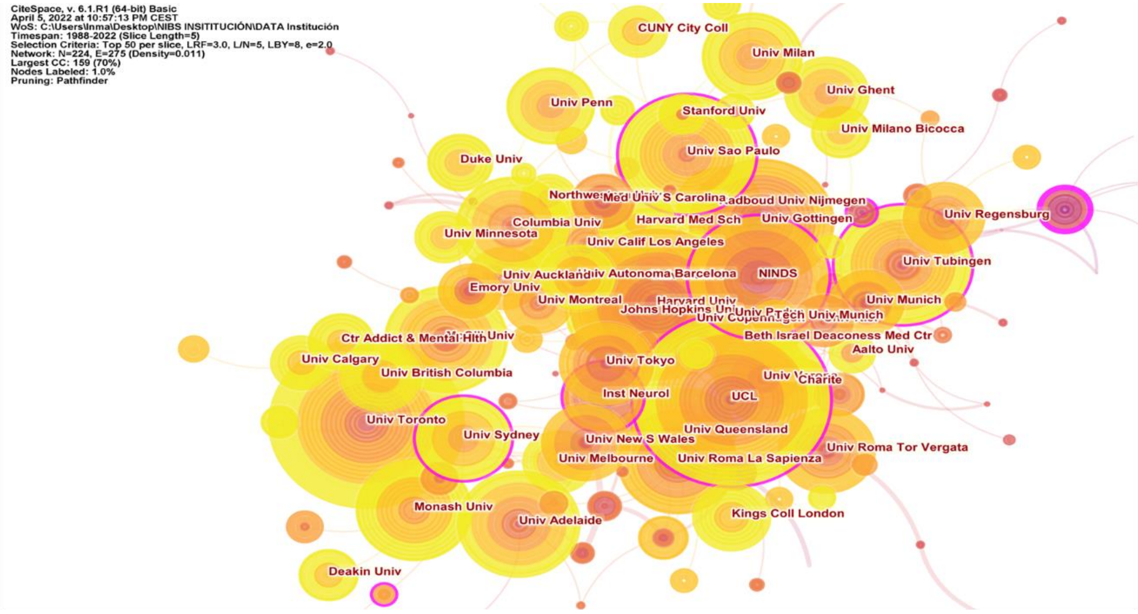


Figure 2. Co-authorship of non-invasive brain stimulation research.



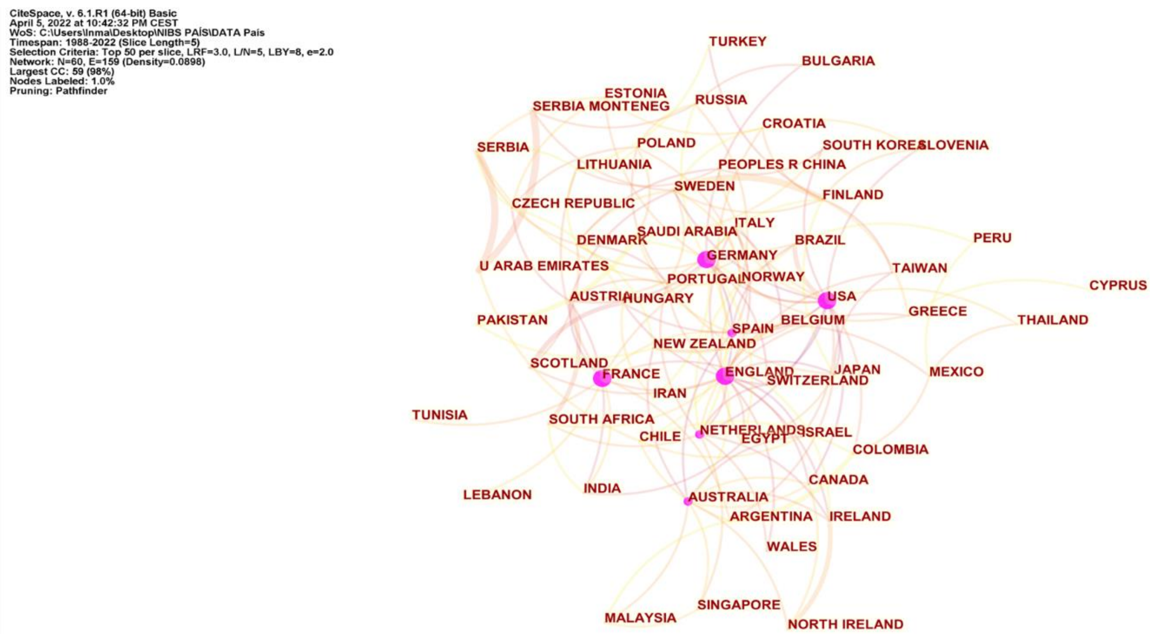
The size of the circle, the thickness of the links and the color of the nodes represent respectively the number of citations, the strength of co-citation between two authors and the different citation years.

Figure 3. Co-institutes in the field of non-invasive brain stimulation.



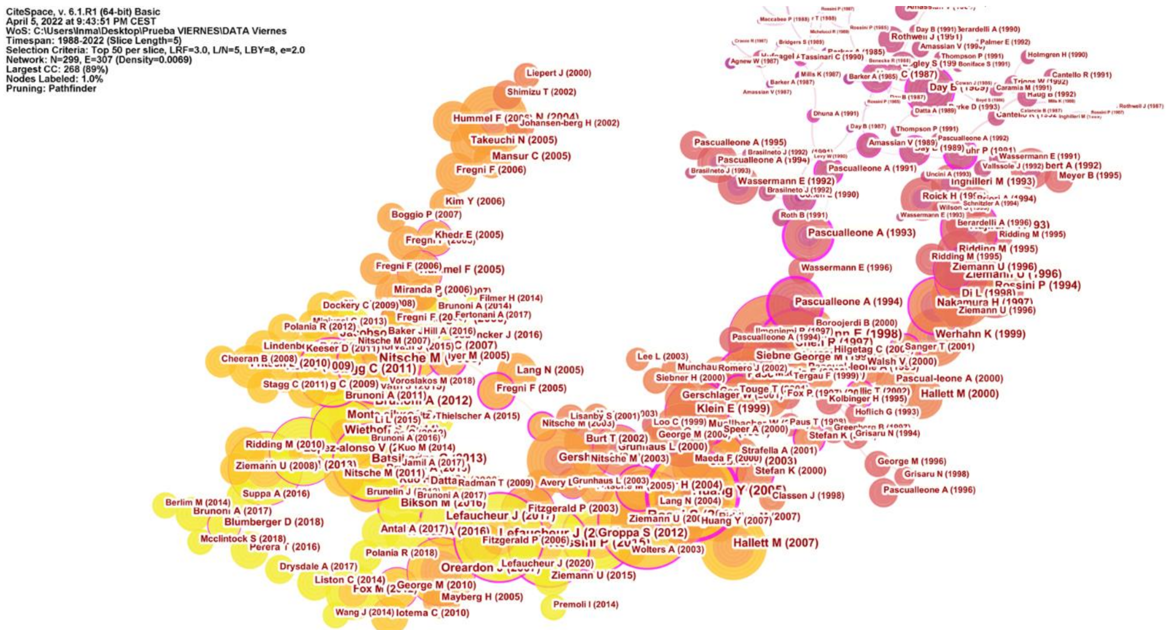
The size of the circle, the thickness of the links and the color of the nodes represent respectively the number of citations, the strength of co-citation between two institutions and the different citation years. External black rings indicate that these institutes have greater centrality

Figure 4. Co-countries in the field of non-invasive brain stimulation.



The thickness of the links represent the strength of co-citation between two countries and the external black rings indicate that these country have greater centrality.

Figure 5. Document co-citation analysis in non-invasive brain stimulation research.



The size of the circle, the thickness of the links and the color of the nodes represent respectively the number of citations, the strength of co-citation between two documents and the different citation years. External black rings indicate that these document have greater centrality