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A Holistic Evaluation of Articles on Neurofeedback Published Between 1975 and 2020: A Bibliometric Analysis

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ABSTRACT

Objective: This study was conducted to provide a holistic view on neurofeedback publications globally and to examine the changes in the characteristics of neurofeedback-related studies through a bibliometric analysis focusing on the period between 1975 and 2020.

Material and methods: All data were obtained from the Web of Science (WoS) database. The term "Neurofeedback" was used as a keyword to search the WoS database. The VOSviewer was used to procure scientometric network visualizations of specific results.

Results: A total of 1480 publications were included, 53.91% of them original articles. The USA dominated the literature with 388 publications followed by Germany and United Kingdom (17.1% and 10%, respectively). Germany was the most productive country with a productivity score of 30.63 followed by USA, Switzerland, Netherlands and Iran (s= 11.87, 10.97, 6.76, 6.72, respectively). The top research fields of these publications were neurosciences and neurology, psychiatry, and engineering. The University of London was revealed as the institution with the most contributions in this field, and the top two authors with the most publications were Sterhl U and Wood G. The Applied Psychophysiology and Biofeedback journal was the foremost journal that published the highest number of articles (n=53, 35.8%). The top cited article was "Efficacy of neurofeedback treatment in ADHD: the effects on inattention, impulsivity and hyperactivity: a meta-analysis" by Arns, M et al. published in 2009. This is the first study to conduct a bibliometric analysis of the neurofeedback literature. The number of publications during this period showed a significant increase annually. All researchers ranking among the top 10 authors were from developed countries.

Conclusion: Scientometric analysis revealed that Germany, USA, United Kingdom, Netherlands, Switzerland, Italy and Canada were closely connected by global bibliometric relationships. Among developing countries, Iran had significantly high contributions to the literature on neurofeedback.

Keywords: neurofeedback; bibliometric analysis; scientometrics; publications.

INTRODUCTION

Neurofeedback, also called neurobiofeedback or neurotherapy, is a term that identifies non-invasive therapeutic interventions that use real-time analysis of brain activity to train individuals the conscious self-regulation of brain function, in addition to providing support for mental processes by measuring brain activities and providing feedback signals (1). Neurofeedback can be performed either by using brain activities measured through electroencephalography (EEG) or functional magnetic resonance imaging (fMRI). EEG-based neurofeedback has the advantages of being relatively more accessible, less expensive and can accommodate for various ambulatory conditions. This approach uses real-time auditory, visual or tactile signals measured from sensors on

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the patient's scalp to reorganize or retrain these brain signals (2). fMRI-based neurofeedback uses the alterations in oxygenation-dependent activity in regions of interest in the brain, and has the advantage of higher localization accuracy and better access to deep subcortical areas of the brain (3). For over four decades, neurofeedback has been practiced in various mental health and/or neurological conditions, including attention deficit, anxiety-depression spectrum, behavior disorders, sleep disorders, learning disabilities, pain management and epilepsy (4). Despite the importance given to publications on neurofeedback, a holistic interpretation of the characteristics of neurofeedback research has not been undertaken. This is an important limitation for the accessibility of the state-of-the-art and also the conduct and planning of future studies, since technological advances have created immense changes.

Bibliometric and scientometric studies are methods to statistically analyze publications in a given field. Bibliometric analysis is a well-established method for the determination of informative studies and groundbreaking advances in a specific scientific field and time period. These studies provide data on the advances in a particular topic and increase the accessibility of said scientific field by evaluating the research productivity of countries, publication characteristics (authors and countries), the distribution of publication types, most cited studies, and the trends of the research itself and its publication (5). The international influence of documents and interdisciplinary information flow can also be established by using citation analysis in bibliometric studies (6). The interest of researchers in neurofeedback has been evolving globally recent years. However, the literature lacks a bibliometric study on scientific production related to neurofeedback. The aim of this study was to evaluate the studies in the field of neurofeedback through the bibliometric method and to provide identification of the tendencies of ongoing research about neurofeedback as an important reference for future studies by focusing on the period between 1975 and 2020.

MATERIAL AND METHODS

All data were obtained from the Web of Science database (WoS, Thomson Reuters, New York, NY, USA). WoS is a website that provides access to multiple databases providing comprehensive citation data and other academic impact information for many different academic disciplines. It is often the go-to data source and is widely used in studies on global research productivity. The WoS database search was performed with the keyword "Neurofeedback" and search criteria was chosen to limit the search within the title of articles. All documents published during the period between 1975 and 2020 were included in the study without any restrictions. Articles conducted and published from the Federal Republic of Germany, Germany, East Germany and West Germany were united under the "Germany" title. The analysis tools present in the WoS database were used to determine publication types, research areas, authors, research institutions, scientific journals, countries, languages and citations. The VOSviewer software (version 1.6.6) was used for scientometric network visualizations and mapping of specific results. Scientometric networks showing related and connected keywords and countries were generated in VOSviewer software. The size of circles in the visualization of network images was based on the frequency of keywords and countries, with more frequent terms forming larger circles compared to less-frequent terms. The distance between two nodes in the country network visualization indicates the proximity of countries with regard to co-authorship ties. The closer the two nodes are to each other, the stronger the collaboration. The strength of co-authoring ties between countries is represented by the thickness of the lines. For the calculation of global productivity scores, the current population data of the countries were obtained from Worldometers (7).

We determined a productivity score for neurofeedback publications for each country by using the following formula (number of publications / population x 10^6) which has been previously reported and utilized in bibliometric studies.

RESULTS

The characteristics of published items

A total of 1480 documents on neurofeedback were found to have been published between 1975 and 2020 as a result of the WoS database search. The majority of these publications consisted of original articles (n=798, 53.91%) followed by meeting abstracts (n=371, 25.06%), proceedings papers (n=134, 9.05%), reviews (n=91, 3.64%), book chapters (n=54, 3.64%), and other publication types (n=95, 6.42%) **(Table 1)**. By language, 1434 (96.8%) of these publications had been documented in English, 26 (1.75%) in German and 7 (0.47%) in French.

Productivity of countries

The United States dominated the literature on neurofeedback with 388 publications (26.2%) followed by Germany and United Kingdom (17.1% and 10%, respectively) **(Figure 1)**. We observed that the top 10 countries publishing the most articles in the field of neurofeedback were developed countries, excluding China, Russia and Iran. Productivity scores revealed that Germany was by far the most productive country with a score of 30.63 followed by USA, Switzerland, Netherlands and Iran (s= 11.87, 10.97, 6.76, 6.72, respectively) **(Figure 2)**.

Research Area, Authors, Institutions and Journals

We also analyzed the research areas in which these neurofeedback studies were published. Neurosciences and neurology (45.6%), psychiatry (18%), and engineering (8.04%) were found to be the most frequent research areas **(Table 1)**. In terms of authors, Strehl U from the Institute of Medical Psychology and Behavioral Neurobiology, University of Tuebingen (Germany) and Wood G from Institute of Psychology, Karl-Franzens-University of Graz, Austria were noted to be most productive authors in the neurofeedback literature with 27 documents each; these two authors produced 1.82% of the total publications in the neurofeedback literature **(Table 1)**. When authors were ranked, all researchers in the top 10 authors list were found to be from developed countries. The University of London was revealed as the foremost institution with a contribution of 79 publications (5.33%), followed by the Eberhard Karls University of Tuebingen and the University of Geneva (4.45% and 2.97%, respectively). All institutions were from developed countries. The *Applied Psychophysiology and Biofeedback* journal was identified as the primary journal in this field with the highest number of publications on neurofeedback (n=201, 13.58%) followed by *Neuroimage* (n=60, 4.05%) and *Frontiers in Human Neuroscience* (n=53, 3.58%).

Evaluation of publications, correlations and citations

The overall H-index of the literature on neurofeedback was calculated to be 68 and the average number of citations per publication was 12.64. The most cited document was a meta-analysis titled "*Efficacy of neurofeedback treatment in ADHD: the effects on inattention, impulsivity and hyperactivity: a meta-analysis*" by Arns, M et al., published in 2009 in the *Clinical EEG and Neuroscience* journal (8). This article was cited 362 times and the average number of yearly citations was 30.17 **(Table 2)**. The meeting which had resulted in the greatest contribution to the field of neurofeedback was the 16th World Congress of Psychophysiology, which was organized by the International Organization of Psychophysiology, with 9 proceedings.

Analysis of Bibliometric Networks

It was shown that a total of 142 different keywords were used in 1480 items. The most frequently used keywords (with total link strength) in the literature were found to be neurofeedback (1020 times), EEG (280), ADHD (151), fMRI (131) biofeedback (129), real-time fMRI (113), brain-computer interface (94), attention (73), self-regulation (67), EEG biofeedback (55). We generated a keyword network infographic from the keyword frequency obtained from the WoS database **(Figure 3)**. The global bibliometric network showed prominent connections between 7 countries, Germany, USA, United Kingdom, Netherlands, Switzerland, Italy and Canada **(Figure 4)**.

DISCUSSION

This study aimed to investigate neurofeedback publications since 1975 to procure a global view on the characteristics of these studies. To the best of our knowledge, this was the first study to conduct a bibliometric analysis of the neurofeedback literature. A comprehensive literature search aimed to include as many related articles as possible was performed in WoS, which revealed 1480 publications in this field between 1975 and 2020. The majority of these studies were original articles and the leading research area was neurosciences and neurology. The top three leading countries that contributed to the literature in terms of publication count were USA, Germany and United Kingdom. The most productive countries with respect to population-based scores were Germany, USA, Switzerland, Netherlands and Iran. The analysis of publications identified the *Applied Psychophysiology and Biofeedback* journal as the leading journal in this field. The number of publications demonstrated a significant increase annually. Germany and USA had the strongest collaborations with other countries, as determined by co-authorship ties.

Bibliometric analyses provide statistical evaluation of academic documents to explore the impact and popularity of specific authors, countries and publications in the scientific community (9). Bibliometrics is commonly used in the academic field to enable reference data that can be used to

understand the dynamics of science and technology, increase the accessibility of contemporary research, identify the innovations of projects, announce research results, and to provide a basis on which researchers can plan future study topics (10). The first bibliometric study was conducted by Campbell in 1896 and the term "bibliometric" was introduced by Pritchard in a paper published in 1969, titled "Statistical Bibliography or Bibliometrics?" (11, 12). To date, bibliometrics has been used to assess and predict trends in various medical conditions, such as cancer, tumor biomarkers, metabolic and neurodegenerative diseases (13). Although the popularity of neurofeedback research and its use has increased in recent decades, to date, there were no available bibliometric studies on neurofeedback that would encourage researchers to plan further studies in this medical field.

Neurofeedback studies originate from the 1930s from the work of Gustave Durup and Alfred Fessard (14). They demonstrated that brain activity could be altered by classical conditioning principles involving the enhancement of relationships between EEG activity (alpha blocking response), behavior and cognitive response via the use of feedback signal(s). Jasper and Shagass reported the first systematic study evaluating the classical conditioning of EEG in 1941 (15). Further publications conducted in the 1960s revealed that alpha-blocking can actually be conditioned and may be associated with some specific cognitive activities of the trained participants (16). During the 1980s and 1990s, neurofeedback studies experienced a severe decrease, particularly due to the poor reliability of techniques used to record brain activity (17). Since the early 2000s, neurofeedback research entered a renaissance with better methodology and the successful results of various clinical and therapeutic studies. Since then neurofeedback therapy has gained more attention in various academic disciplines, particularly psychiatry and neurology (18). Consistent with this, we found that neurofeedback was used widely in neuroscience disciplines such as, neurology and psychiatry. With respect to the effectiveness of neurofeedback in brain disorders, attempts have been made to utilize neurofeedback training in neurology-related conditions including attention deficit hyperactivity disorder (ADHD), autistic spectrum disorders, depression, anxiety and epilepsy (4, 19). We reported that EEG and ADHD were the trend keywords that received the most citations. Neurofeedback therapy is accepted as a rehabilitation approach in the treatment of ADHD, and is suggested to have a role in the normalization of behavior without being dependent on medication or behavioral therapy. This treatment is effective in reducing hyperactivity, increasing focus and consequently improving measures of attention (4). Therefore, it is understandable that ADHD and neurofeedback were both found to be trending keywords.

We also demonstrated that the number of publications and citations on neurofeedback had increased rapidly in recent years. In parallel with increased social media networks and socioeconomic development, the increase in awareness about neurofeedback training has led to an increase in the number of patients receiving this treatment and an increase in the number of publications, especially original articles. The analysis of publications showed that the *Applied Psychophysiology and Biofeedback* journal was the main journal in the field of neurofeedback and played a significant role in the distribution of new knowledge pertaining to neurofeedback. "Efficacy of neurofeedback treatment in ADHD: the effects on inattention, impulsivity and hyperactivity: a meta-analysis" by Arns, M et al. was the most important study according to the total citations (8). The most important study regarding to average number of citations per year was "Closed-loop brain training: the science of neurofeedback" by Sitaram R. et al. published in 2017 (20). We also showed that Germany and USA had the highest collaboration levels with other countries, as determined by co-authorship ties. For USA, collaboration was mostly with Germany, Wales and Canada. This indicates that geographical distance is not among the main factors affecting cooperation between countries.

In evaluating country-based data, we observed that the countries with the most publications in the literature were USA and Germany, followed by the United Kingdom and the Netherlands. Our data also demonstrates that, not only developed countries but also developing countries have had a considerable role in this topic, with data showing that Iran, Russia and China have contributed to the literature at a greater degree compared to other developed countries. This may be related to the acceleration of access to new publications in developing countries as a result of internet-based knowledge transfer, open access articles, and possibly the increase in social media usage. The University of London and the Eberhard Karls University of Tuebingen were determined to be the most productive institutions in the neurofeedback field. The most active authors, with regard to the

number of publications, were Strehl U and Wood G. It is of note that all researchers in the top 10 of the authors list were from developed countries. This is likely associated with later procurement of necessary devices and researchers in developing countries; however, it is also evident that the economic might of developed countries enable greater investment in research, increasing overall productivity of the country and individual researchers. We believe that researchers from less-developed countries should be supported by public funds to instate the infrastructure necessary for such studies, since it is arguable that research in this field requires relatively lower levels of continuous funding.

Several limitations of the current work should be mentioned. First, the study was limited to the WoS database. Despite the leading status of WoS and its inarguable role in global research, the omission of other data sources limit the generalizability of our data to all academic databases. Secondly, even though the majority of items were written in English (96.8%), demonstrating that capturing a comprehensive picture was possible through this assessment, the study was completed using only English keywords, causing the omission of studies that did not provide English titles. Lastly, since the nature of bibliometric studies are cross-sectional, our results may be significantly influenced by the time period included in the analysis, and therefore, the conclusions could change if data were drawn from a different or shorter time period.

CONCLUSION

In conclusion, this was the first study to conduct a bibliometric analysis of the neurofeedback literature. We demonstrated the global productivity on neurofeedback research from 1975 to 2020. USA and Germany dominated the literature and were at the top of the productivity rankings. The main research areas were found to be neuroscience including neurology and psychiatry. All researchers in the top 10 authors list were from developed countries. We reported that Germany, USA, United Kingdom, Netherlands, Switzerland, Italy and Canada were closely connected by global bibliometric relationships. Of note, Iran had significantly high contributions to the literature on neurofeedback among developing countries, especially when assessed with the productivity score.

Author contributions

YHO and FE designed the study; YHO and MS collected the data; FE and MS analyzed and interpreted the data; YHO, FE and MS wrote the manuscript. All authors contributed to drafting and revising the manuscript and provided final approval of the publication version.

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FIGURE LEGENDS

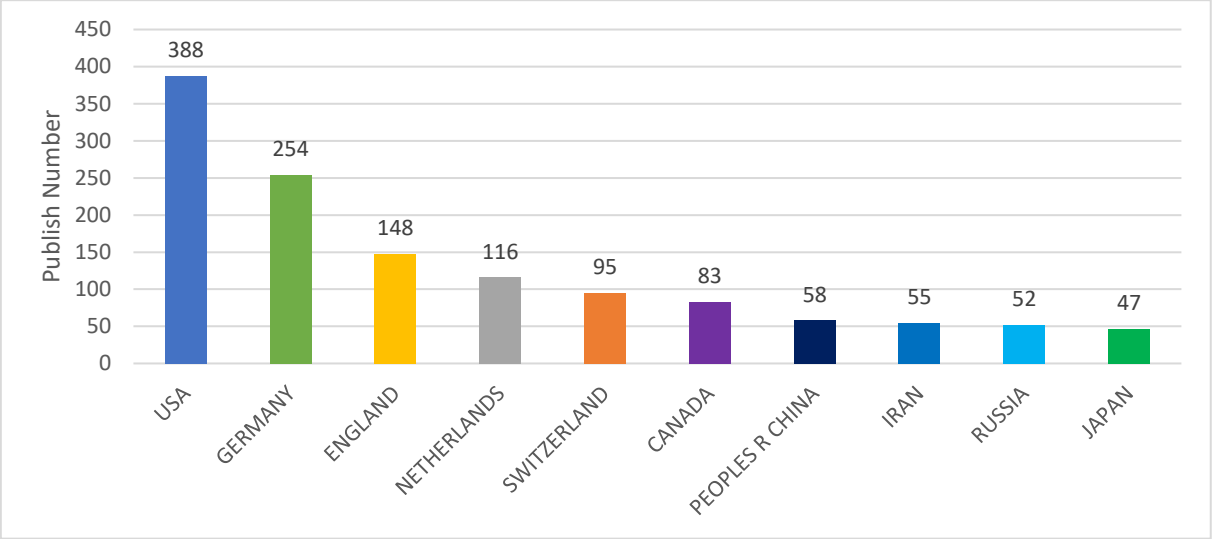

Figure 1. **Top 10 countries by publication number in neurofeedback literature**

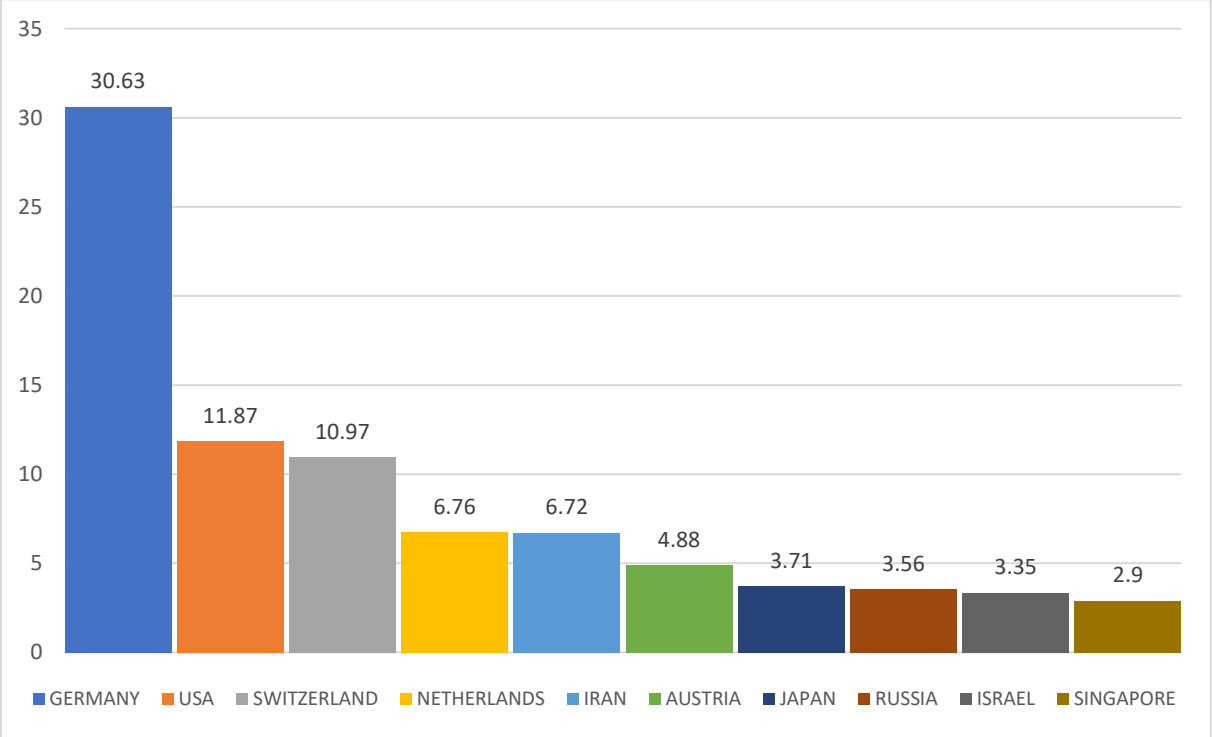

Figure 2. **Top 10 countries by global productivity scores in neurofeedback literature**

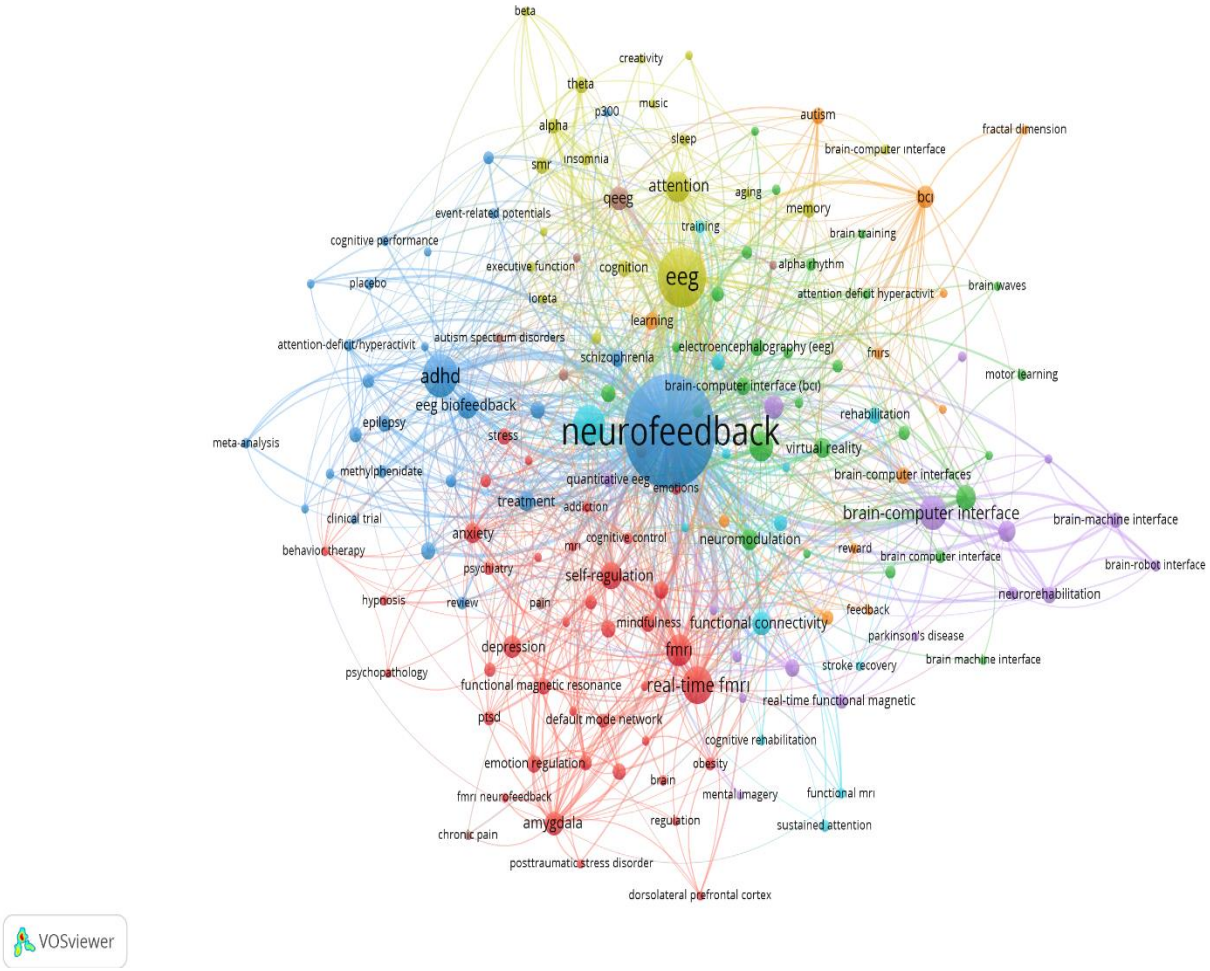

Figure 3. **Keyword network in neurofeedback literature**

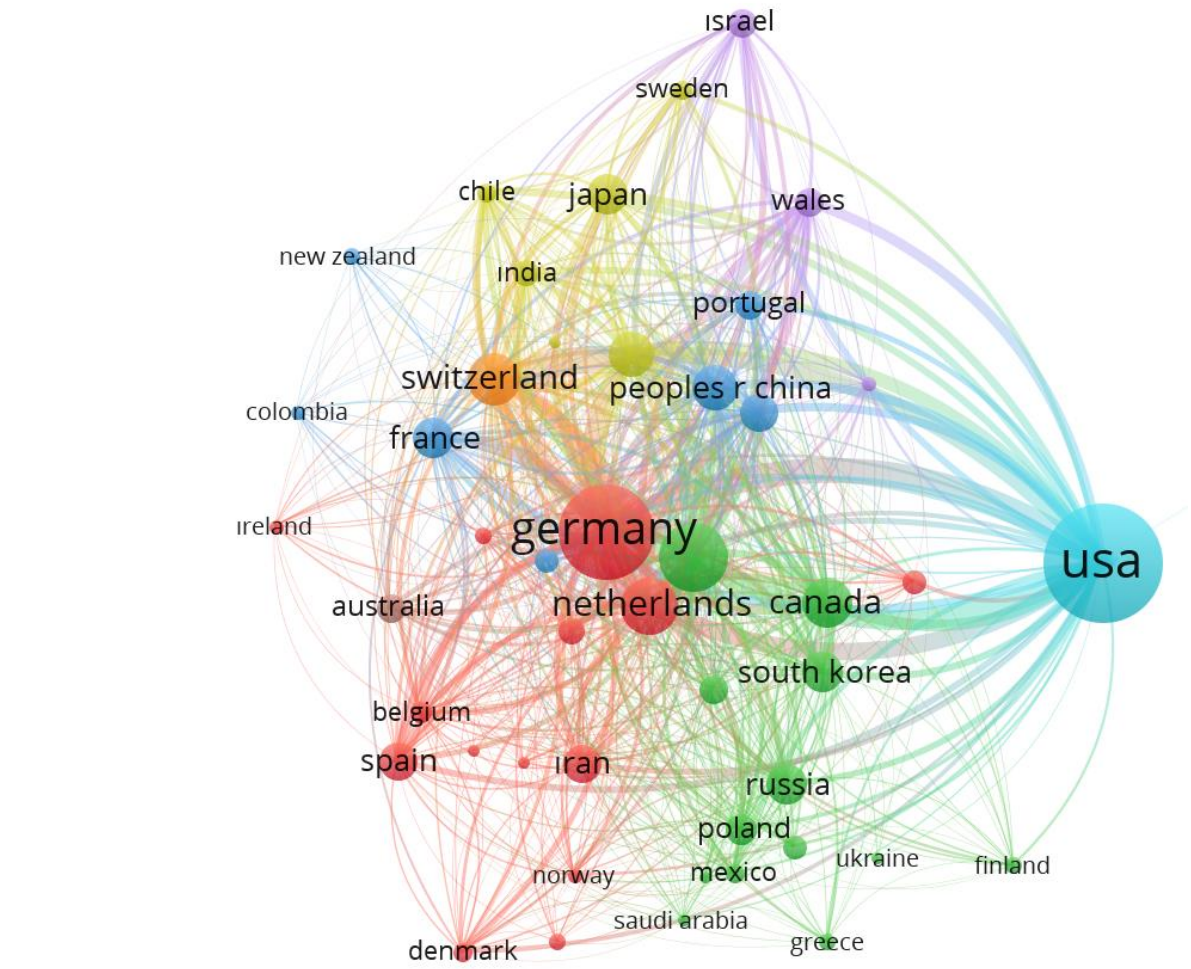

Figure 4. **Scientometric network of the countries cooperating in neurofeedback publications**

Table 1. **Types of publication, top research areas, authors, institutions and journals in neurofeedback literature**

	Number	% of 1480 articles
Document Type		
Article	798	53,91
Meeting Abstract	371	25,06
Proceedings Paper	134	9,05
Review	91	6,14
Book Chapter	54	3,64
Editorial Material	44	2,97
Letter	20	1,35
Correction	15	1,01
Early Access	9	0,6
Book Review	7	0,47
Research Areas		
Neurosciences Neurology	675	45,60
Psychiatry	267	18,04
Engineering	119	8,04
Radiology Nuclear Medicine Medical Imaging	80	5,40
Computer Science	69	4,66
Physiology	63	4,25
Behavioral Sciences	58	3,91
Science Technology	42	2,83
Rehabilitation	39	2,63
Pediatrics	37	2,50
Authors		
Strehl U	27	1,82
Wood G	27	1,82
Brandeis D	25	1,68
Gruzelier Jh	25	1,68
Bodurka J	24	1,62
Scharnowski F	24	1,62
Neuper C	23	1,55
Arns M	22	1,48
Kober Se	22	1,48
Birbaumer N	21	1,41
Institutions		
University of London	79	5,33
Eberhard Karls Universıty of Tuebingen	66	4,45
Unıversity of Geneva	44	2,97
Unıversity of Zurich	43	2,9
Ruprecht Karls Universıty Heidelberg	40	2,7
Maastricht University	37	2,5
Centre National De La Recherche Scientifique Cnrs	31	2,09
University of California System	31	2,09
University of Graz	30	2,02
Radboud University Nijmegen	29	1,95
Journals		
Applied Psychophysiology and Biofeedback	201	13,58
Neuroimage	60	4,05
Frontiers in Human Neuroscience	53	3,58
International Journal of Psychophysiology	40	2,70
Biological Psychiatry	29	1,95
Clinical Eeg And Neuroscience	27	1,82
Plos One	22	1,48
European Psychiatry	18	1,21
Clinical Neurophysiology	17	1,14
Neuroscience	17	1,14

Table 2. **The most cited manuscripts in the neurofeedback literature**

ARTICLE	AUTHORS	JOURNAL NAME	YEAR	TOTAL CITATION	AVERAGE CITATION PER YEAR
Efficacy of Neurofeedback Treatment in ADHD: The Effects on Inattention, Impulsivity and Hyperactivity: a Meta-Analysis	By: Arns, Martijn; de Ridder, Sabine; Strehl, Ute; et al.	Clinical Eeg And Neuroscience	2009	364	30,3
Neurofeedback treatment for attention-deficit/hyperactivity disorder in children: A comparison with methylphenidate	By: Fuchs, T; Birbaumer, N; Lutzenberger, W; et al.	Applied Psychophysiology and Biofeedback	2003	233	12,94
Perceptual Learning Incepted by Decoded fMRI Neurofeedback Without Stimulus Presentation	By: Shibata, Kazuhisa; Watanabe, Takeo; Sasaki, Yuka; et al.	Science	2011	221	22,10
The effect of training distinct neurofeedback protocols on aspects of cognitive performance	By: Vernon, D; Egner, T; Cooper, N; et al.	International Journal of Psychophysiology	2003	214	11,89
Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance	By: Zoefel, Benedikt; Huster, Rene J.; Herrmann, Christoph S.	Neuroimage	2011	201	20,10
Evaluation of The Effectiveness of Eeg Neurofeedback Training for Adhd In A Clinical Setting as Measured by Changes in Tova Scores, Behavioral Ratings, And Wısc-R Performance	By: Lubar, Jf; Swartwood, Mo; Swartwood, Jn; et al.	Biofeedback and Self-Regulation	1995	200	7,69
Real-time fMRI neurofeedback: Progress and challenges	By: Sulzer, J.; Haller, S.; Scharnowski, F.; et al.	Neuroimage	2013	198	24,75
Increasing individual upper alpha power by neurofeedback improves cognitive performance in human subjects	By: Hanslmayr, S; Sauseng, P; Doppelmayr, M; et al.	Applied Psychophysiology and Biofeedback	2005	197	12,31
Is neurofeedback an efficacious treatment for ADHD? A randomised controlled clinical trial	By: Gevensleben, Holger; Holl, Birgit; Albrecht, Bjoern; et al.	Journal of Child Psychology and Psychiatry	2005	182	15,17
Closed-loop brain training: the science of neurofeedback	By: Sitaram, Ranganatha; Ros, Tomas; Stoeckel, Luke; et al.	Nature Reviews Neuroscience	2017	174	43,5