NEUROSCIENCE RESEARCH NOTES

OPEN ACCESS | DATA NOTES ISSN: 2576-828X

Bibliometric analysis of neurofeedback research from 2000 to 2022

Siti Atiyah Ali [1,2,*], Mazira Mohamad Ghazali [3], Nurfaizatul Aisyah Ab Aziz [3] and Humaira Nisar [1,2]

[1] Centre for Healthcare Science and Technology, Universiti Tunku Abdul Rahman, Bandar Sungai Long, 43000 Kajang, Malaysia.
[2] Department of Electronic Engineering, Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, 31900, Perak, Malaysia.
[3] Department of Neuroscience & Brain & Behaviour Cluster, Universiti Sains Malaysia, 16150, Kelantan, Malaysia.
* Correspondence: atiyahali90@yahoo.com.my; Tel.: +6013-3153685

Received: 14 June 2023; **Accepted:** 19 December 2023; **Published:** 16 March 2024
Edited by: Indranath Chatterjee (Tongmyong University, South Korea)
Reviewed by: Ahmed Alsharif (Universiti Teknologi Malaysia, Malaysia);
Panlekha Rungruang (Mahidol University, Thailand)
https://doi.org/10.31117/neuroscirn.v7i1.265

ABSTRACT: The application of neurofeedback is gaining increasing interest among neuroscientists as a potential neurorehabilitation approach in cases of various neuro-related functional abnormalities. Discovering the current state of research and identifying gaps in the field of neurofeedback is an essential step in planning and mapping out future research efforts. This bibliometric analysis paper aims to identify the publications and research in neurofeedback from 2000 to 2022. A comprehensive Scopus database search was conducted using the keyword "neurofeedback" and relevant publications from 2000 to 2022 were retrieved. Bibliometric analyses were performed using the Harzing's Publish or Perish and VOSviewer software programmes. The number of retrieved documents was 1835. The number of publications has shown a steadily increasing trend since 2000, with a prominent spike in publications in 2014–2015, indicating a sudden interest in neurofeedback. Among the retrieved documents, 50.3% were related to neuroscience, 23.7% related to medicine, and 13.1% related to psychology. The main contributors to this research come from the United States (24.7%), Germany (13.7%), the United Kingdom (9.4%), and Switzerland (4.9%). Based on the network visualisation of author keywords, the most frequently occurring keywords were neurofeedback, real-time functional magnetic resonance imaging (fMRI), brain-computer interface (BCI), neuromodulation, and neurofeedback training. This bibliometric analysis presents the current status, knowledge base, and future neurofeedback study directions. These findings will benefit future researchers interested in applying neurofeedback as a potential neurorehabilitation approach for a wider population.

Keywords: Neurofeedback; Neurorehabilitation; Neuroscience

©2024 Ali *et al*. for use and distribution according to the Creative Commons Attribution (CC BY-NC 4.0) license (https://creativecommons.org/licenses/by-nc/4.0/), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original author and source are credited.

1.0 INTRODUCTION

The regulation of brainwaves is not new to the world of neuroscience. It is believed that abnormal brainwave patterns can be normalised back through training. Neurofeedback is a non-invasive neurotherapy that measures brainwave activity and provides a real-time feedback signal (Marzbani et al., 2016). Neurofeedback was introduced in the early 1940s, with researchers using classical conditioning methods to induce changes in EEG readings, specifically alpha-blocking responses. These findings led to the hypothesis that specific conditioning could elicit changes in brain activity (Arns et al., 2014).

In the last 20 years, research on the topic of neurofeedback has gradually gained attention among clinicians as a potential neurotherapy in improving specific symptoms associated with cognitive and behavioural abnormalities. The neurofeedback mechanism performs feedback training to correct the abnormal brainwave patterns and return them to normalcy. There are five different brainwaves, and each of them has specific frequencies: delta (1 – 3 Hz), theta (4 – 7 Hz), alpha (8 – 12 Hz), beta (13 – 30 Hz), and gamma (> 30 Hz). Each brainwave represents a different state of brain activity. Delta is dominant when the mind is unconscious or deep asleep, while theta is most commonly found during dreamless sleep, inattention, trance meditation, or drowsiness. In a state of relaxation, your brain exhibits alpha brainwaves, while when you're alert or focused, your brain generates beta brainwaves. Gamma is dominant during learning and concentration. However, some neurological issues related to cognitive or neurodevelopmental disorders may lead to abnormal dominance of brain activity. For instance, attention-deficit hyperactivity disorder (ADHD) is associated with an elevated theta and beta ratio, while schizophrenia is linked to reduced alpha with enhanced beta. Alzheimer's disease is characterised by an improved delta/theta ratio with a reduced alpha/beta ratio (Adamou et al., 2020; Itil, 1977; Newson & Thiagarajan, 2019; Picken et al., 2020).

However, each brain brainwave's dominance is not unique to a specific neurological disorder, as there may be cross-similarities in brainwave dominance across different disorders. Given that neural maturity varies throughout adulthood or ageing, it is not ascertained that the dominance of brainwaves remains the same. In this regard, neurofeedback is a neurotherapy method that uses a certain brainwave as a treatment protocol for a series of training sessions. It aims to alleviate certain cognitive states. No reinforcement is given to subjects whose brainwaves produce abnormal patterns in response to certain stimuli until the brainwaves improve. The most common treatment protocol in neurofeedback includes theta, alpha, beta, and the alpha/theta ratio (Vernon, 2005). Several studies have produced varying results regarding the effectiveness of neurofeedback in improving cognitive function and behavioural performance (Loriette et al., 2021; Tseng et al., 2021; Vernon, 2005; Zandi Mehran et al., 2015). Despite neurofeedback's effectiveness having attracted attention for more in-depth research worldwide, relatively few clinical health facilities still provide neurofeedback as an option for neurotherapy. Instead, it is more readily available at private facilities, which can make it inaccessible to some people. The lack of randomised controlled trial (RCT) studies in neurofeedback may be a contributing factor. The lack of RCTs means there is less definite evidence of the efficacy of neurofeedback for treatment purposes (Janssen et al., 2016).

Given the growing number of studies on neurofeedback as a neurotherapy in many healthcare settings, a bibliometric analysis of these studies could be beneficial in revealing research trends in neurofeedback. This analysis can help future researchers identify specific areas of neurofeedback that can be explored further. Additionally, this type of analysis has been widely used to represent trend data of research in other areas, such as neuromarketing (Alsharif et al., 2021 and 2023b), neuroscience (Lin et al., 2022) and neurorehabilitation (Tsiamalou et al., 2022). To the best of our knowledge, no bibliometric analysis studies have been conducted in neurofeedback. Therefore, there is no comprehensive overview of the scope of neurofeedback publications and trends in this field over the past few decades. A bibliometric study focuses on the document analysis of citation-based measurement of journals, authors, and institutions in a specific area. The statistical data obtained from bibliometric studies provide insights into research significance, the influence of journals, and the contributions of authors, institutions, and countries within a particular research domain (Szomszor et al., 2021). Therefore, to track the advancement of neurofeedback research, it is essential to conduct a bibliometric study to analyse and visualise the literature on neurofeedback research from its inception to the present. Furthermore, quantitative bibliometrics analysis provides the progress of neurofeedback research and identifies research hotspots, research collaboration, management strategies, and cutting-edge trends in neurofeedback research (Liu et al., 2022). This

bibliometric research paper explored research articles from the Scopus database, specifically on neurofeedback over the past 22 years, from 2000 to 2022, to address the following research questions:

Research question 1: What is the distribution data of the types, source types, languages and areas of neurofeedback documents published between 2000 and 2022?

Research question 2: What is the annual number of neurofeedback publications from 2000 to 2022?

Research question 3: Which publisher/journal has been the most active in publishing neurofeedback documents?

Research question 4: What are the top author keywords most frequently used in neurofeedback documents?

Research question 5: Which countries, authors, and organisations/institutes have been the most active in neurofeedback research over the last 22 years?

Research question 6: Which articles are the most cited in the neurofeedback research between 2000 and 2022?

2.0 METHODS

The search strategy was centred around the keyword "neurofeedback". Neurofeedback research is very limited, thus, a general search encompassing all research related to neurofeedback was conducted. This search was performed using the Scopus database, covering 2000 to 2022. Scopus was selected as the search platform due to its larger database, comprehensive coverage, and inclusion of a wide range of topics compared to other search databases (Alsharif et al., 2022). The selected timeframe was decided because the information within this period remains relevant and worth exploring. Twenty-two years is still relatively short considering the ever-evolving nature of neurofeedback techniques and protocols. All types of documents were included in the search such as articles, reviews, editorials, book chapters, notes, letters, short surveys and errata. Bibliometric analysis can be considered a new profile analysis of publication data. It has been applied in many areas, including medical research (Manoj Kumar et al., 2023), neuromarketing (Alsharif et al., 2023a), health technology (Luo et al., 2022), and other areas. To ensure the thoroughness of our analysis, two investigators independently reviewed each article for inclusion and exclusion. No articles were excluded as long as they were related to neurofeedback. **Figure 1** summarises the methodology used in this bibliometric analysis.

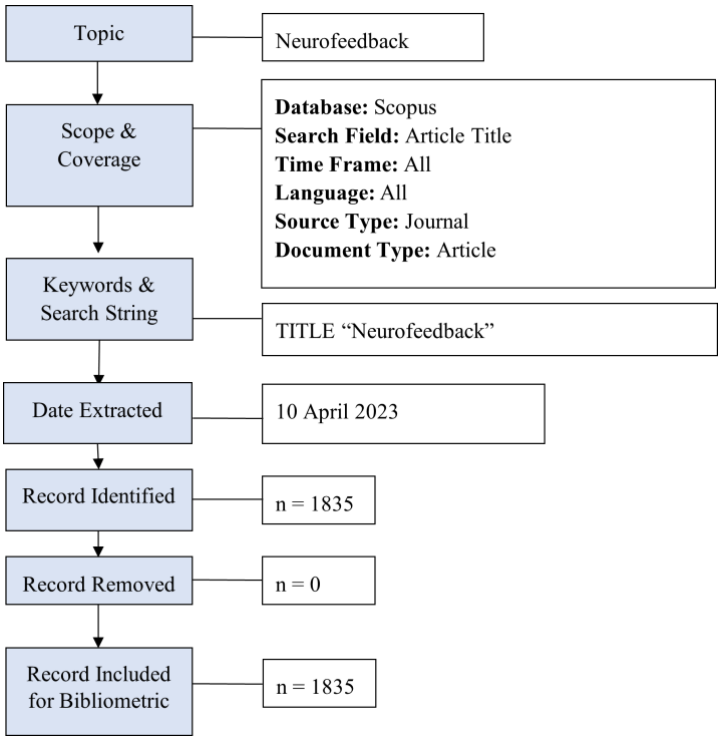


Figure 1: Flow diagram of the search strategy

2.1 Data analysis and visualisation

The bibliometric analysis of citation metrics was conducted using Harzing's Publish or Perish open-source software. Data retrieved from the Scopus database were exported to Excel for tabular data analysis. The visualisation of data in the form of figures was performed using the VOSviewer programme, which is user-friendly. The data exported from the Scopus database and included in this paper are as follows:

1) Types of documents
2) Source types of documents
3) Areas of documents
4) Languages of documents
5) Number of publications per year
6) The most active source of neurofeedback-related publications
7) Top author keywords
8) Top 20 countries contributing to neurofeedback publications
9) The 20 most productive authors with the highest number of citations
10) Top 20 organisations/institutes contributing to the neurofeedback publications (obtained from Harzing's Publish or Perish)
11) Citation metrics and the most highly-cited articles (Obtained from Harzing's Publish or Perish)

3.0 RESULTS

3.1 Number and types of document publications

The search yielded a total of 1,835 documents related to neurofeedback. In terms of the number of publications on neurofeedback per year, there was an increasing trend starting from the year 2000 and continuing to 2022, as shown in **Figure 2** below. The highest number of publications occurred in 2022, with 190 publications. Meanwhile, the second-highest count was in 2021 with 188 publications, followed by 2020 with 173 publications. The lowest publication count was in 2000, with just two publications. From 2000 to 2009, less than ten publications were published each year. However, there has been a continuous increase in publication numbers, reflecting the growing interest in neurofeedback applications to enhance the self-regulatory capacity of brain wave activities. In 2014, there was a significant spike in publications, possibly attributed to a heightened public interest in neurofeedback as a potential cognitive rehabilitation therapy for psychological problems. Its non-invasive and safe nature contributed to this surge.

Table 1 shows an overview of the types of document publications related to neurofeedback. Out of the total publications, 1,342 (73%) were research articles, while review articles accounted for 286 (16%), and editorials for 79 (4%). Other document types made up less than 4% of the total publications. The source types of document publications are shown in **Table 2**. An overwhelming 96% of source types originated from journals, while the remaining 4% was distributed among books, book series, and conference proceedings.

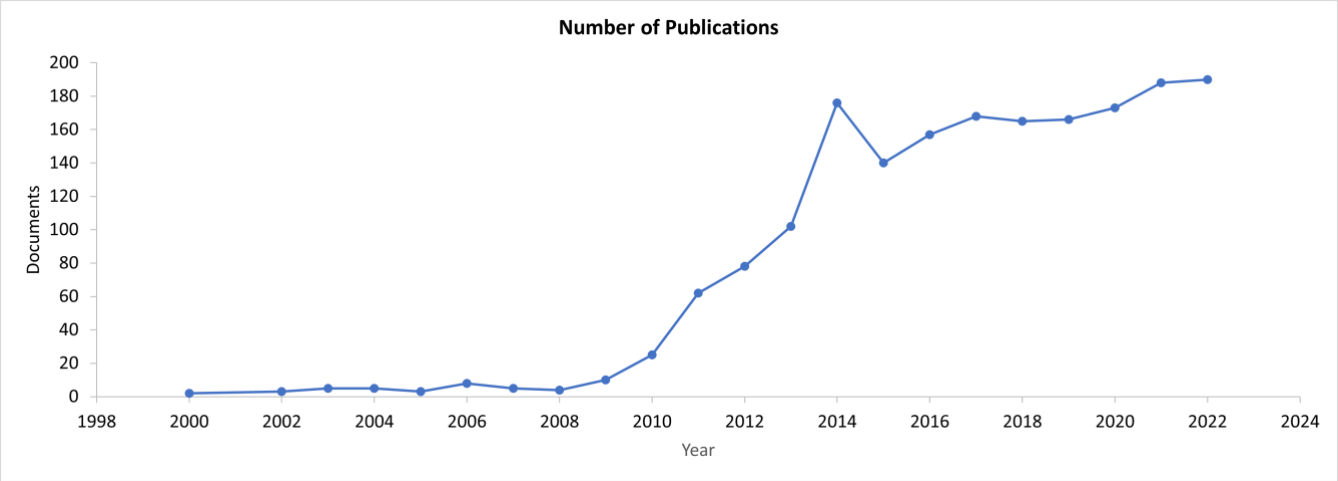


Figure 2: Number of publications per year from 2000 to 2022

Table 1: Types of documents

Document Type	Number of documents	Percentage (%)
Article	1342	73%
Review	286	16%
Editorial	79	4%
Book chapter	55	3%
Note	24	1%
Conference	19	1%
Letter	15	1%
Short survey	13	1%
Erratum	2	0%

Table 2: Source types of document publications

Source Type	Total Publications	Percentage (%)
Journal	1757	96%
Book	33	2%
Book Series	33	2%
Conference Proceeding	12	1%
Total	**1835**	**100.00**

3.2 Most active journals

Figure 3 shows a graphical representation of the annual publication numbers from active sources, spanning 2000 to 2022. The highest number of publications came from the "Frontiers in Human Neuroscience", with 172 publications (**Figure 3**). Next was Neuroimage, with 121 publications; the third highest was Neuroregulation, with 80 publications.

3.3 Subject area of document publications

The pie chart illustrating the percentage distribution of subject areas is shown in **Figure 4** below. The subject area of neuroscience was mainly dominant, accounting for 50.3% of all publications (1,835 documents). In addition, the subject area of medicine was ranked second highest, with 865 publications, making up 23.7% of the total. The psychology subject area secured the third-highest position, with 479 publications, constituting 13.1% of the total publications. All other subject areas, including biochemistry, genetics and molecular biology, health professions, engineering, and computer science, represented below 5% of the total publications. The unlabelled proportions of the pie chart sections corresponded to subject areas with less than 0.5% of document publications.

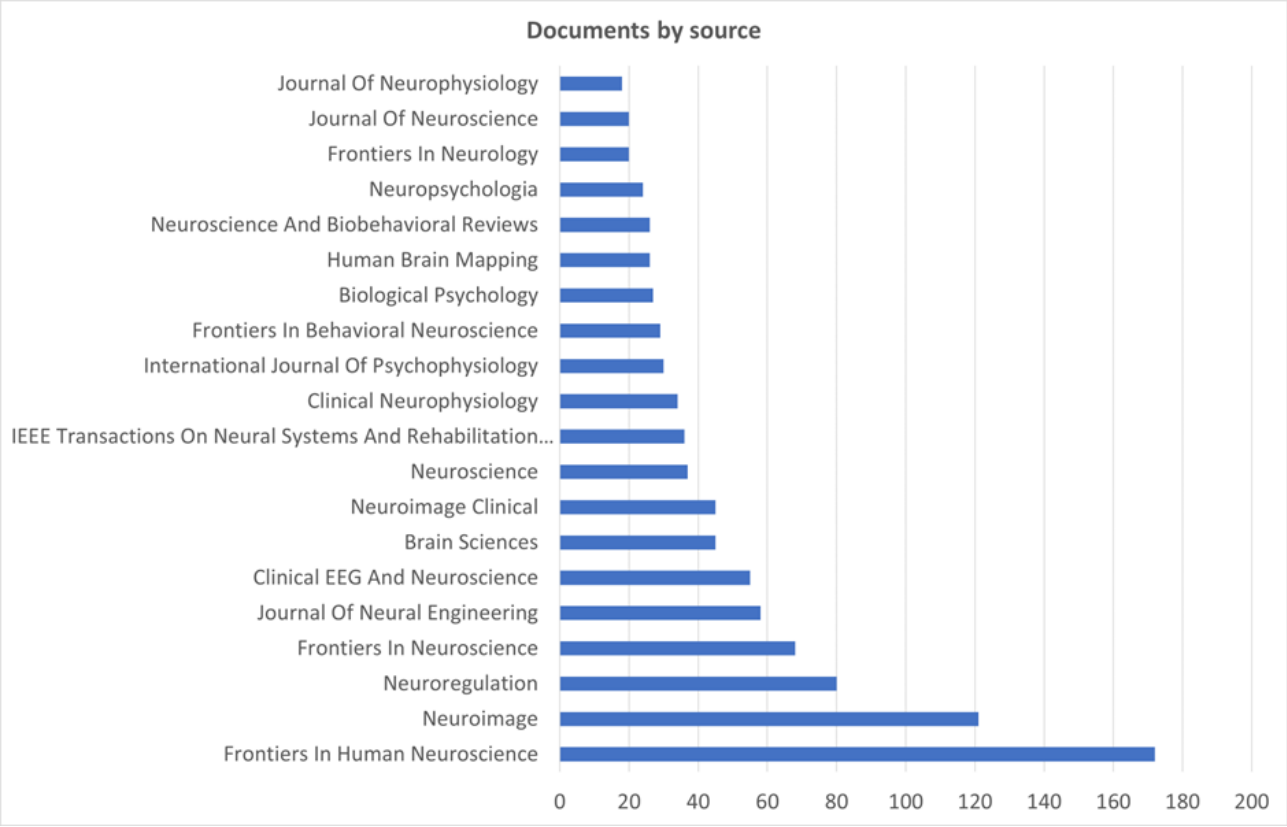
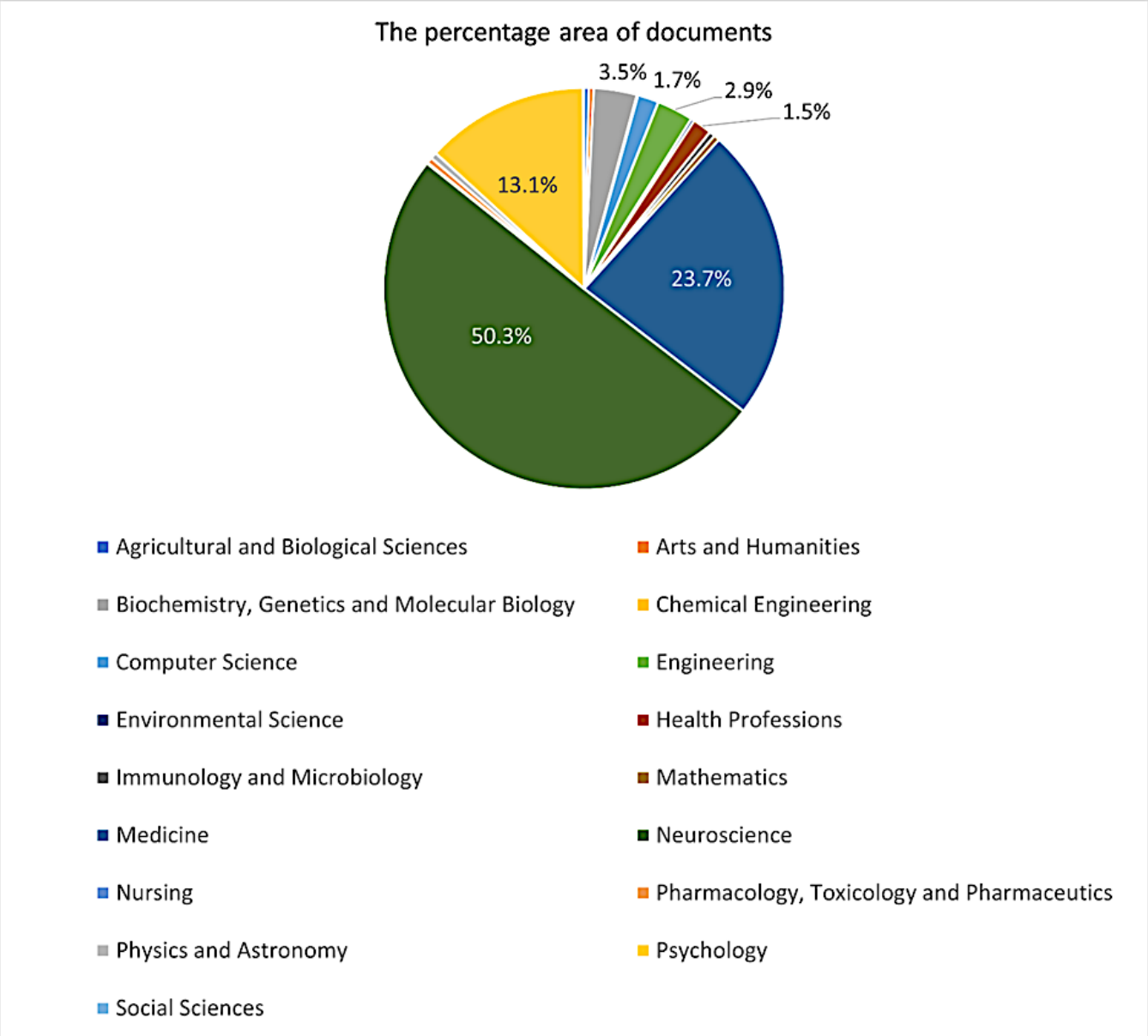


Figure 3: Most active source of neurofeedback related publications



**Unlabelled percentage has less than 0.5 % proportions.*

Figure 4: The pie chart percentage area of documents

3.4 The most active institutions

A total of 31 institutions have published articles related to neurofeedback. The top 20 most productive institutions are shown in **Table 3**. The University of Tübingen held the first rank with 104 publications, representing 4.0% of the total. Universiteit Maastricht followed closely with 55 publications, accounting for 2.1%, and Universität Zürich was in the third position with 51 publications, making up 2.0% of the total. Among the top 20 active institutions, four are in the United Kingdom (UK), the United States of America (USA), and Switzerland, three are in Germany, two are in France, and one is in China, the Netherlands, and Austria.

Table 3: Top 20 organisations/institutes contributed to the neurofeedback publication

Affiliation	No of citations	Percentage (%)
University of Tübingen, Germany	104	4.0
Universiteit Maastricht, Netherlands	55	2.1
Universität Zürich, Switzerland	51	2.0
University of Geneva, Switzerland	43	1.6
Central Institute of Mental Health, Germany	43	1.6
University College London, UK	39	1.5
Harvard Medical School, USA	36	1.4
Universität Heidelberg, Germany	36	1.4
The French National Centre for Scientific Research, France	33	1.3
Swiss Federal Institute of Technology Lausanne, Switzerland	32	1.2
University of Graz, Austria	30	1.1
ETH Zürich, Switzerland	30	1.1
King's College London, United Kingdom	29	1.1
Cardiff University, UK	28	1.1
Inserm, France	27	1.0
University of Oxford Medical Sciences Division, UK	27	1.0
Yale University, USA	27	1.0
Laureate Institute for Brain Research, USA	27	1.0
Yale School of Medicine, USA	25	1.0
Beijing Normal University, China	25	1.0
TOTAL of citations (including out of 20 top list)	**2613**	**100.00**

3.5 The most active countries, affiliations, and funding source institutions

A total of 62 countries have contributed to the documents retrieved. The top 20 countries that contributed to the highest number of citations and publications are listed in **Table 4**, with the highest rank of affiliations and funding source institutions. In contrast, the network visualisation of countries is represented in **Table 4** and **Figure 5**. The USA secured the top position in active publications, with 665 publications, 21,262 citations, and a citation percentage of 24.7%. Harvard Medical School ranked the top affiliation, while the National Institutes of Health (NIH) led as the most productive funding source agency in the USA. Ranked second was Germany with 369 publications, 15,352 citations and 13.7% citation percentage, and the University of Tübingen was the top affiliation. The United Kingdom (UK) was the third most active country, contributing 253 publications, 10,770 citations, and a citation percentage of 9.4%. University College London took the lead as the highest-affiliated publication institution in neurofeedback. The most productive funding sources for Germany and the UK were the German Research Foundation (DFG) and the Medical Research Council, respectively.

The network visualisation of countries in **Figure 5** was interpreted by observing the thickness of the line connecting the countries. The thicker the line connection between the countries, the higher the strength of research collaboration. As visualised in **Figure 5**, international collaboration in neurofeedback research showed the highest strength of cooperation among the USA, UK, Netherlands, and Germany.

3.6 The citation metrics and most cited articles

The citation metrics obtained from the Scopus database are listed in **Table 5** below. Between 2000 and 2022, there were 1,835 publications with 52,765 citations.

Table 4: Top 20 countries, affiliations and funding source institutions contributed to the neurofeedback publications

No.	Organisation	Total Publications	Citation	Percentage (%)	Top affiliations	The productive funding source agencies/ institutions	Publications of agencies/ institutions
1	United States	665	21262	24.7	Harvard Medical School	National Institutes of Health (NIH)	133
2	Germany	369	15352	13.7	University of Tübingen	German Research Foundation (DFG)	98
3	United Kingdom	253	10770	9.4	University College London	Medical Research Council (MRC)	42
4	Switzerland	131	4867	5.0	University of Geneva	Swiss National Science Foundation (SNSF)	47
5	Netherlands	135	6646	4.9	University of Maastricht	Netherlands Organisation for Scientific Research	11
6	Italy	116	5003	4.7	San Camillo Forlanini Hospital	Undefined	Undefined
7	Canada	115	3795	4.3	University of Toronto	Canadian Institutes of Health Research	19
8	Japan	97	2033	4.3	Keio University	Japan Agency for Medical Research and Development	48
9	Austria	61	1471	3.6	University of Graz	University of Graz	5
10	China	127	2090	3.1	Beijing Normal University	National Natural Science Foundation of China	16
11	Spain	53	1789	2.3	undefined	Ministry of Science and Innovation	3
12	Australia	52	1586	2.0	The University of Sydney	National Health and Medical Research Council (NHMRC)	3
13	Sweden	28	774	2.0	Institute of Karolinska	undefined	Undefined
14	Brazil	33	576	1.9	D'Or Institute for Research and Teaching	National council for scientific and technological development	12
15	Israel	49	1234	1.7	undefined	undefined	Undefined
16	France	82	2617	1.3	CNRS National Center for Scientific Research	National Research Agency	12
17	Chile	25	1590	1.2	undefined	National Commission for Scientific and Technological Research Chile	19
18	Belgium	27	906	1.1	undefined	undefined	Undefined
19	India	29	1290	1.1	Sree Chitra Tirunal Institute for Medical Sciences and Technology	Department of Science and Technology, Ministry of Science and Technology	9
20	Norway	17	422	1.1	undefined	undefined	Undefined

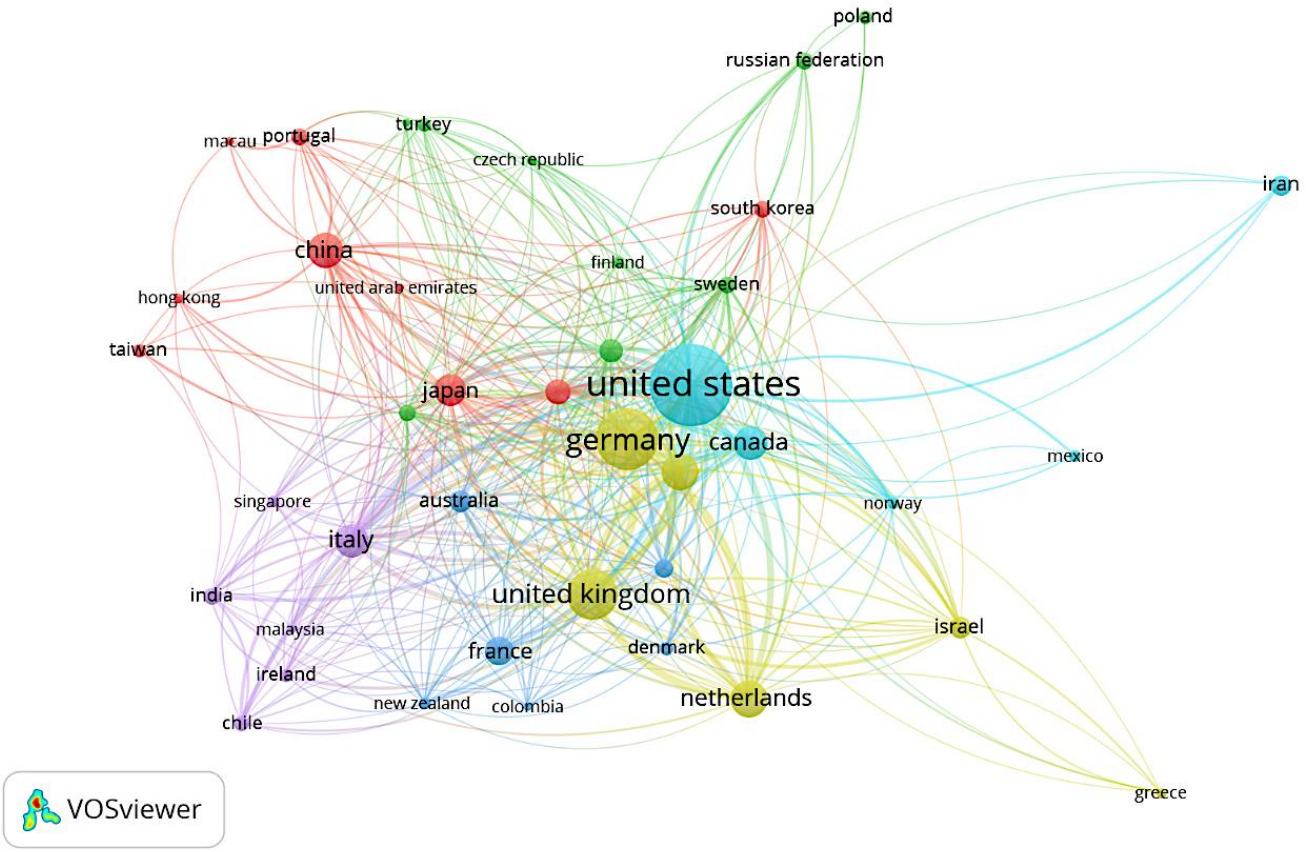


Figure 5: Network visualisation of countries

Table 5: Citations Metrics

Metrics	Data
Publication years	2000-2022
Citation years	23 (2000-2022)
Papers	1835
Citations	52765
Citations/year	2294.13
Citations/paper	28.75
Papers/author	4.67
h-index	108
g-index	156

3.7 Authorship analysis

The top 20 highly cited articles are shown in **Table 6**. The most cited article was titled 'Efficacy of Neurofeedback Treatment in ADHD: The Effects on Inattention, Impulsivity, and Hyperactivity: A Meta-Analysis', published in 2009 in Clinical EEG and Neuroscience, with a total of 538 citations. Next, an article entitled 'Closed-loop Brain Training: The Science of Neurofeedback', published in Nature Reviews Neuroscience in 2017, with 532 citations, while 'The Effect of Training Distinct Neurofeedback Protocols on Aspects of Cognitive Performance', published in 2003 in International Journal of Psychophysiology, also had 532 citations. Among the top 20 articles, seven were published in the Neuroimage journal. The total number of authors involved in neurofeedback publications was 1,435, but this authorship analysis included only the top 20 authors with the highest citations, as shown in (**Table 7**). The most active author was Birbaumer N., with 33 publications and 3,372 citations. The second most active author was Sitaram R., with 25 publications and 2,233 citations, followed by Weiskopf N., with 12 publications and 2,146 citations. The rest of the authors also had many publications but received less than 2,000 citations each. On average, each of the top 20 authors had accumulated 1,413 citations.

3.8 Keywords analysis

The keyword analysis conducted during the initial data collection using the VOSviewer programme determined the top 20 keywords. The link strength between keyword interactions is shown in **Table 8**. All the keywords listed were associated with neurofeedback, with each keyword exhibiting a high connection strength between each keyword. The connections of each

keyword were visually represented in the VOSviewer programme of network visualisation map of the author keywords within the initial dataset of 1835 documents, as shown in **Figure 6**. From the network visualisation map analysis, the results were clustered into 11 clusters based on the author's keywords. These 11 clusters are listed in **Figure 7**. The themes of each cluster were presented according to the author's opinions. Cluster 1 is the targeted brain area in neurofeedback, Cluster 2 is the target group, Cluster 3 is functional activity, and Cluster 4 is another aspect of behaviour. Cluster 5 to Cluster 8 are neurofeedback tools and modalities, and lastly, Cluster 9 to Cluster 11 are targeted outputs and findings in neurofeedback.

Table 6: Top 20 highly cited articles

No.	Authors	Title	Journal	Year	Cites	Cites/ year
1	Arns M, de Ridder S, Strehl U, Breteler M, and Coenen A.	Efficacy of Neurofeedback Treatment in ADHD: The Effects on Inattention, Impulsivity and Hyperactivity: A Meta-Analysis	Clinical EEG and Neuroscience	2009	538	38.43
2	Sitaram, R., Ros, T., Stoeckel, L. et al.	Closed-loop brain training: the science of neurofeedback	Nature Reviews Neuroscience	2017	532	88.67
3	Vernon D, Egner T, Cooper N, Compton T, Neilands C, Sheri A, and Gruzelier J.	The effect of training distinct neurofeedback protocols on aspects of cognitive performance	International Journal of Psychophysiology	2003	331	16.55
4	Zoefel B, Huster RJ, and Herrmann CS.	Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance	NeuroImage	2011	329	27.42
5	Weiskopf N, Veit R, Erb M, Mathiak K, Grodd W, Goebel R, Birbaumer N.	Physiological self-regulation of regional brain activity using real-time functional magnetic resonance imaging (fMRI): methodology and exemplary data	NeuroImage	2003	325	16.25
6	Sulzer J, Haller S, Scharnowski F, Weiskopf N, et al.	Real-time fMRI neurofeedback: Progress and challenges	NeuroImage	2013	309	30.90
7	Gruzelier JH	EEG-neurofeedback for optimising performance. I: A review of cognitive and affective outcome in healthy participants	Neuroscience & Biobehavioral Reviews	2014	307	34.11
8	Egner T and Gruzelier JH	EEG Biofeedback of low beta band components: frequency-specific effects on variables of attention and event-related brain potentials	Clinical Neurophysiology	2004	286	15.05
9	Caria A, Veit R, Sitaram R, Lotze M, et al.	Regulation of anterior insular cortex activity using real-time fMRI	Neuroimage	2007	281	17.56
10	Ullsperger M, Fischer AG and Nigbur R.	Neural mechanisms and temporal dynamics of performance monitoring	Trends in Cognitive Sciences	2014	263	29.22
11	Arns M, Heinrich H and Strehl U	Evaluation of neurofeedback in ADHD: The long and winding road	Biological Psychology	2014	256	28.44
12	Marzbani H, Marateb H R, Mansourian M	Methodological Note: Neurofeedback: A Comprehensive Review on System Design, Methodology and Clinical Applications	Basic and Clinical Neuroscience	2016	254	36.29
13	Stermann MB	Basic Concepts and Clinical Findings in the Treatment of Seizure Disorders with EEG Operant Conditioning	Clinical Electro-encephalography	2000	250	10.87

(continued on the next page)

14	Weiskopf N	Real-time fMRI and its application to neurofeedback	Neuroimage	2012	224	20.36
15	Weiskopf N, Scharnowski F, Veit R, Goebel R, Birbaumer N and Mathiak K.	Self-regulation of local brain activity using real-time functional magnetic resonance imaging (fMRI)	Journal of Physiology-Paris	2004	215	11.32
16	Johnston SJ, Boehm SG, Healy D, Goebel R and Linden DEJ	Neurofeedback: A promising tool for the self-regulation of emotion networks	Neuroimage	2010	207	15.92
17	Ruiz S, Lee S, Soekadar S, Caria A, et al.	Neurofeedback: A promising tool for the self-regulation of emotion networks	NeuroImage	2013	205	20.50
18	Siegle JH, López AC, Patel YA, Abramov K, et al.	Open Ephys: an open-source, plugin-based platform for multichannel electrophysiology	Journal of Neural Engineering	2017	199	33.17
19	Tobias E and Gruzelier JH	Ecological validity of neurofeedback modulation of slow wave EEG enhances musical performance	Neuroreport	2003	195	9.75
20	Lévesque J, Beauregard M and Mensour B.	Effect of neurofeedback training on the neural substrates of selective attention in children with attention-deficit/hyperactivity disorder: A functional magnetic resonance imaging study	Neuroscience Letters	2006	191	11.24

Table 7: The 20 most productive authors with the highest number of citations

Author's Name	No. of Documents	No. of Citations	Average of Total Citations
Birbaumer N.	33	3372	101
Sitaram R.	25	2233	89
Weiskopf N.	12	2146	179
Veit R.	12	1655	138
Scharnowski F.	19	1647	87
Goebel R.	26	1618	62
Gruzelier J.H.	17	1560	92
Ros T.	18	1348	75
Strehl U.	14	1339	96
Sulzer J.	9	1227	136
Heinrich H.	18	1204	67
Haller S.	8	1163	145
Linden D.E.J.	21	1026	49
Egner T.	5	995	40
Blefari M.L.	5	983	197
Caria A.	9	969	108
Arns M.	10	966	10
Neuper C.	24	959	40
Mathiak K.	15	930	62
Gevensleben H.	14	924	66

Table 8: The number of keywords and total link strength

Keyword	Number of keywords	Total link strength
Neurofeedback	725	1809
EEG	185	465
Real-Time fMRI	110	314
fMRI	101	279
Brain-Computer Interface	96	250
ADHD	67	179
Electroencephalography	60	156
Biofeedback	56	157
Stroke	55	171
Motor Imagery	54	144
Functional Connectivity	51	144
Self-Regulation	50	159
Attention	48	140
Neuromodulation	47	140
Amygdala	46	164
Depression	45	142
Learning	36	98
Neurofeedback Training	32	57
Neuroimaging	30	80
Neurorehabilitation	30	92

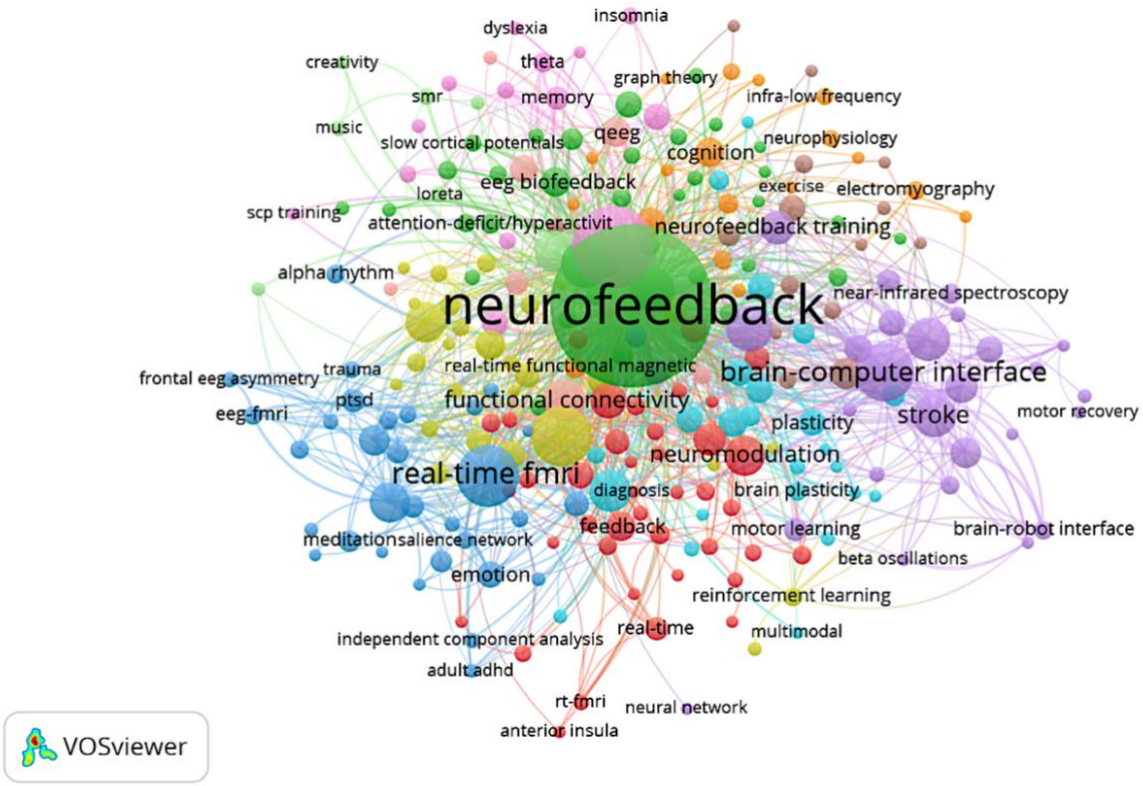


Figure 6: VOSviewer of the network visualisation map of the author keywords.

Cluster 1 (40 items)	Cluster 2 (37 items)	Cluster 3 (32 items)	Cluster 4 (28 items)
• Adolescents • Anterior insular • Basal ganglia • Behaviour • Brain • Brain oscillations • Cerebellum • Closed loop • Connectivity • Cortex	• ADHD • Attention-deficit hyperactivity disorder • Autism • Autism spectrum disorder • Biofeedback • Children • Chronic pain • Cognitive impairment • EEG biofeedback • EEG neurofeedback	• Adult ADHD • Alpha oscillations • Alpha rhythm • Amygdala • Brain connectivity • Default mode network • Dorsolateral Prefrontal • EEG-fMRI • Emotion • Emotion regulation	• Addiction • Adolescence • Anterior Cingulate Cortex • Anxiety • Cognitive control • Cortisol • Decision making • Depression • Dopamine
Cluster 5 (27 items)	**Cluster 6 (24 items)**	**Cluster 7 (18 items)**	**Cluster 8 (15 items)**
• Action observation • Beta oscillations • Brain Computer interface • Brain machine interface • Brain-robot interface • Electrocorticography • EEG • Event related desynchronization • Functional electrical stimulation • Functional infra-red spectroscopy	• Brain computer interface • Brain plasticity • Brain training • Closed loop • Cognitive training • Coherence • Comorbidity • EEG • Event related desynchronization • fMRI	• Affect • Aging • Brain computer interface • Cognition • Decoding • Elderly • Electromyography • Exercise • Graph theory • Infra-low frequency	• BCI • BMI • Brain stimulation • Cognitive enhancement • Dysphagia • Executive functions • Motor • Motor control • MRI • Near Infrared spectroscopy
Cluster 9 (14 items)	**Cluster 10 (11 items)**	**Cluster 11 (7 items)**	
• Alpha • Consolidation • Dyslexia • EEG • Gamma • Hippocampus • Implicit learning • Insomnia • Memory • Prediction	• Biomarkers • Cognitive performance • ERP • Fibromyalgia • Functional connectivity • Machine learning • Motor cortex • Psychopathology • Psychotherapy • qEEG	• Attention • Creativity • Emotions • Heart rate variability • LORETA • Music • SMR	

Figure 7: The classification of author keyword clusters retrieved from VOSviewer analysis

As indicated by the darker colour nodes (**Figure 8**), the early literature on neurofeedback around 2016 primarily focused on EEG biofeedback, motor learning, and operant conditioning. However, with the advancement of research from 2017 to 2019, the keyword literature shifted its focus towards EEG-fMRI, functional connectivity, infra-low frequency, insomnia, and virtual reality. This shift in keyword trends can be attributed to the advancement of neurofeedback modalities, which now incorporate real-time functional fMRI and EEG. The co-word density visualisation of author keywords clearly showed a prominent map position with the most profound colour map for neurofeedback, functional connectivity, real-time fMRI, MRI, stroke, and EEG (**Figure 9**). Similarly, the author's keyword strength in **Table 8** shows comparable results to the overlay map and density visualisation in **Figures 8** and **9**. The keywords "neurofeedback", "EEG", "real-time MRI", and "MRI" exhibited the highest total link strength and were among the most frequently occurring keywords.

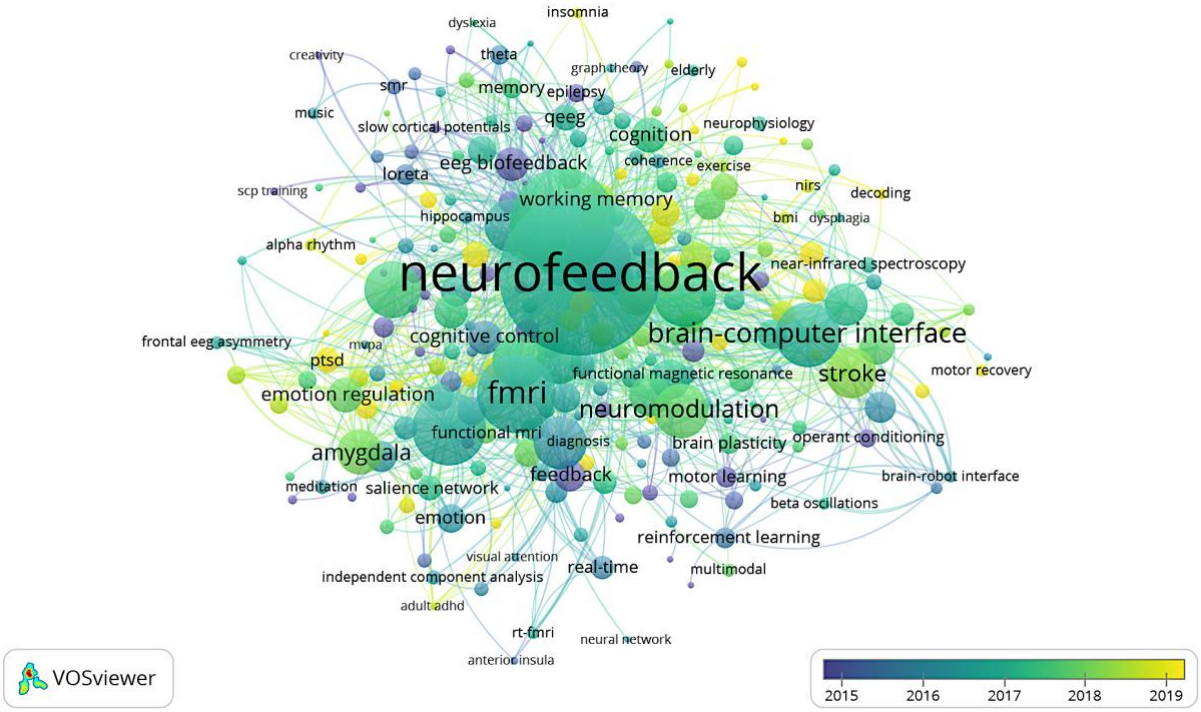


Figure 8: The overlay map of the author keywords

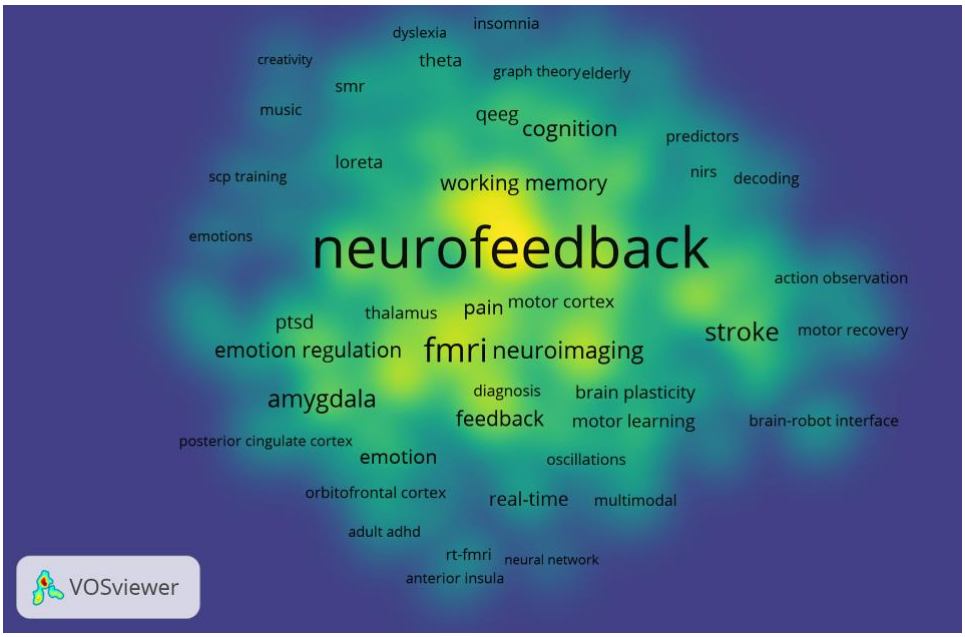


Figure 9: Co-word density visualisation of the author keywords

4.0 DISCUSSION

Bibliometric studies on neurofeedback are limited, with only a few published recently. To the best of our knowledge, this is the first bibliometric analysis paper that provides a comprehensive overview of the number of citations, contributors (countries, journals, authors), and types of documents related to neurofeedback. However, this paper is limited to a general bibliometric analysis of neurofeedback-related documents. It does not explicitly address any kinds of neurofeedback modalities, such as EEG, real-time fMRI, or magnetoencephalography (MEG). This is because the neurofeedback study is still in its early stages, and a general bibliometric analysis is prioritised now. The second limitation is that this paper only covers bibliometric analysis from 2000 to 2022 and does not include the early years of neurofeedback research in the 1960s and 1970s (Othmer, 2015). This is because in the early years of neurofeedback, many studies were animal-based, with few focusing on human studies in a clinical setting. Thus, this study provides a significant dataset of bibliometric information, including the areas of neurofeedback research, and highlights prominent researchers and institutions involved in human neurofeedback studies. This information can serve as a reference for future researchers to guide their efforts before beginning to explore any gaps in neurofeedback research areas. This comprehensive bibliometric analysis is expected to be a valuable contribution to the field, aiding in the development of new and improved neurofeedback protocols and methods.

Figure 2 shows a consistent increase in the number of publications on neurofeedback since 2000. This trend is likely due to the growing interest in neurofeedback as a treatment for various conditions and the development of new and improved neurofeedback modalities. The increasing affordability and accessibility of neurofeedback may also contribute to the trend. As healthcare companies invest in research and development (R&D), the cost of neurofeedback has decreased, making it more available to those who benefit from it.

According to the highly cited articles in **Table 6**, EEG neurofeedback is more commonly used than real-time fMRI neurofeedback. This is likely because EEG is less expensive and widely available than real-time fMRI. However, real-time fMRI is now seen as the future of neurofeedback, as evidenced by the increasing number of author keywords related to real-time fMRI in **Table 8**, **Figure 8**, and **Figure 9**. We hope that future researchers will consider this paper an opportunity to identify gaps in neurofeedback studies that warrant further investigation.

5.0 CONCLUSIONS

This bibliometric analysis of neurofeedback research shows a steady increase in publications over the past 22 years. Although the total number of publications remains relatively modest (1,835), the analysis identifies several active research areas within neurofeedback. These areas include cognitive performance and the various protocols and methods used in neurofeedback. More than 73% of the documents were published as research articles, suggesting that original research is being conducted in this field. It is also worth noting that the growth of neurofeedback research has increased worldwide, including in Asian countries. Overall, neurofeedback is recognised as a promising neurotherapy for addressing cognitive and behavioural disorders, with the potential for further exploration to provide support for its efficacy in improving cognitive impairments. This bibliometric study offers a comprehensive analysis of neurofeedback research, which may be useful for clinicians and researchers, particularly those in neuroscience and psychology.

Ethical consideration:
This bibliometric analysis study did not include human or non-human subjects; thus, no requirement of ethical approval is needed.

Acknowledgements:
This study was not funded by any agency.

Author Contributions:
Conceptualisation and designation by S.A.A.; bibliometric data analysis by S.A.A. and M.M.G.; writing, review and editing by S.A.A., M.M.G., N.A.A.A. and H.N..

Conflicts of Interest:
The authors declare no conflict of interest.

References

Adamou, M., Fullen, T., & Jones, S. L. (2020). EEG for Diagnosis of Adult ADHD: A Systematic Review With Narrative Analysis. *Frontiers in Psychiatry, 11,* 871. https://doi.org/10.3389/fpsyt.2020.00871

Alsharif, A. H., Md Salleh, N. Z., Baharun, R., & Rami Hashem E, A. (2021). Neuromarketing research in the last five years: a bibliometric analysis. *Cogent Business & Management, 8*(1), 1978620. https://doi.org/10.1080/23311975.2021.1978620

Alsharif, A. H., Md Salleh, N. Z., Alrawad, M., & Lutfi, A. (2023a). Exploring global trends and future directions in advertising research: A focus on consumer behavior. *Current Psychology.* https://doi.org/10.1007/s12144-023-04812-w

Alsharif, A. H., Md Salleh, N. Z., & Pilelienė, L. (2023b). A Comprehensive Bibliometric Analysis of fNIRS and fMRI Technology in Neuromarketing. *Scientific Annals of Economics and Business, 70*(3), 459–472. https://doi.org/10.47743/saeb-2023-0031

Alsharif, A. H., Md Salleh, N. Z., Baharun, R., Abuhassna, H., & Alharthi Rami Hashem, E. (2022). A Global Research Trends of Neuromarketing: 2015-2020. *Ravista de Communication, 21*(1), 15–32. http://dx.doi.org/10.26441/RC21.1-2022-A1

Arns, M., Heinrich, H., & Strehl, U. (2014). Evaluation of neurofeedback in ADHD: The long and winding road. *Biological Psychology, 95*, 108–115. https://doi.org/10.1016/j.biopsycho.2013.11.013

Itil, T. M. (1977). Qualitative and Quantitative EEG Findings in Schizophrenia. *Schizophrenia Bulletin, 3*(1), 61–79. https://doi.org/10.1093/schbul/3.1.61

Janssen, T. W. P., Bink, M., Geladé, K., van Mourik, R., Maras, A., & Oosterlaan, J. (2016). A randomized controlled trial into the effects of neurofeedback, methylphenidate, and physical activity on EEG power spectra in children with ADHD. *Journal of Child Psychology and Psychiatry, 57*(5), 633–644. https://doi.org/10.1111/jcpp.12517

Lin, C.-L., Chen, Z., Jiang, X., Chen, G. L., & Jin, P. (2022). Roles and Research Trends of Neuroscience on Major Information Systems Journal: A Bibliometric and Content Analysis. *Frontiers in Neuroscience, 16*, 872532. https://doi.org/10.3389/fnins.2022.872532

Liu, X., Zhao, S., Tan, L., Tan, Y., Wang, Y., Ye, Z., Hou, C., Xu, Y., Liu, S., & Wang, G. (2022). Frontier and hot topics in electrochemiluminescence sensing technology based on CiteSpace bibliometric analysis. *Biosensors and Bioelectronics, 201,* 113932. https://doi.org/10.1016/j.bios.2021.113932

Loriette, C., Ziane, C., & Ben Hamed, S. (2021). Neurofeedback for cognitive enhancement and intervention and brain plasticity. *Revue Neurologique, 177*(9), 1133–1144. https://doi.org/10.1016/j.neurol.2021.08.004

Luo, X., Wu, Y., Niu, L., & Huang, L. (2022). Bibliometric Analysis of Health Technology Research: 1990~2020. *International Journal of Environmental Research and Public Health, 19*(15), 9044. https://doi.org/10.3390/ijerph19159044

Manoj Kumar L., George, R. J., & P.S., A. (2023). Bibliometric Analysis for Medical Research. *Indian Journal of Psychological Medicine, 45*(3), 277–282. https://doi.org/10.1177/02537176221103617

Marzbani, H., Marateb, H., & Mansourian, M. (2016). Methodological Note: Neurofeedback: A Comprehensive Review on System Design, Methodology and Clinical Applications. *Basic and Clinical Neuroscience Journal, 7*(2), 143–158. https://doi.org/10.15412/J.BCN.03070208

Newson, J. J., & Thiagarajan, T. C. (2019). EEG Frequency Bands in Psychiatric Disorders: A Review of Resting State Studies. *Frontiers in Human Neuroscience, 12*. 521. https://doi.org/10.3389/fnhum.2018.00521

Othmer, S. (2015). History of neurofeedback. In *Restoring the Brain* (pp. 23–50). CRC Press. https://doi.org/10.1201/b18671-4

Picken, C., Clarke, A. R., Barry, R. J., McCarthy, R., & Selikowitz, M. (2020). The Theta/Beta Ratio as an Index of Cognitive Processing in Adults With the Combined Type of Attention Deficit Hyperactivity Disorder. *Clinical EEG and Neuroscience, 51*(3), 167–173. https://doi.org/10.1177/1550059419895142

Szomszor, M., Adams, J., Fry, R., Gebert, C., Pendlebury, D. A., Potter, R. W. K., & Rogers, G. (2021). Interpreting Bibliometric Data. *Frontiers in Research Metrics and Analytics, 5*, 628703. https://doi.org/10.3389/frma.2020.628703

Tseng, Y.-H., Tamura, K., & Okamoto, T. (2021). Neurofeedback training improves episodic and semantic long-term memory performance. *Scientific Reports, 11*(1), 17274. https://doi.org/10.1038/s41598-021-96726-5

Tsiamalou, A., Dardiotis, E., Paterakis, K., Fotakopoulos, G., Liampas, I., Sgantzos, M., Siokas, V., & Brotis, A. G. (2022). EEG in Neurorehabilitation: A Bibliometric Analysis and Content Review. *Neurology International, 14*(4), 1046–1061. https://doi.org/10.3390/neurolint14040084

Vernon, D. J. (2005). Can Neurofeedback Training Enhance Performance? An Evaluation of the Evidence with Implications for Future Research. *Applied Psychophysiology and Biofeedback, 30*(4), 347–364. https://doi.org/10.1007/s10484-005-8421-4

Zandi Mehran, Y., Firoozabadi, M., & Rostami, R. (2015). Improvement of Neurofeedback Therapy for Improved Attention Through Facilitation of Brain Activity Using Local Sinusoidal Extremely Low Frequency Magnetic Field Exposure. *Clinical EEG and Neuroscience, 46*(2), 100–112. https://doi.org/10.1177/1550059414524403