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Original Article

Opportunities and Challenges of Multimodal Electroencephalography and Functional Near Infrared Spectroscopy in Neurological Disorders: A Bibliometric Analysis from 2005 to 2024

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Abstract

Background and objectives: Multimodal applications combining electroencephalogram (EEG) and functional near-infrared spectroscopy (fNIRS) are widely used in cognitive neuroscience and have progressively been applied to clinical applications, such as the joint diagnosis of amyotrophic lateral sclerosis, Alzheimer's disease, and pediatric epilepsy. This study conducted a bibliometric analysis of EEG-fNIRS synchronization techniques over the past 20 years. The aim was to clarify their diagnostic and therapeutic value in clinical applications, particularly in the neurological system, and to guide future research and development trends.

Methods: This study utilized the Web of Science Core Collection database to analyze documents published between January 1, 2005, and May 13, 2024. CiteSpace and VOSviewer were employed for visual analyses of co-author relationships, keywords, citation patterns, and journal distributions. By overlaying dual-map diagrams and analyzing annual publication trends, the study identified research hotspots, development trends, and the evolution of EEG-fNIRS technology.

Results: A total of 645 articles and reviews from 55 countries were analyzed. The USA contributed the most publications. The team led by Michela Balconi at the Catholic University of the Sacred Heart published the highest number of papers. Frontiers in Human Neuroscience had the greatest number of publications, while NeuroImage had the highest citation impact. Recent research has primarily focused on the application of neuroimaging and neurophysiological techniques (e.g., EEG, fNIRS, functional magnetic resonance imaging), brain activation, and brain-computer interface.

Conclusions: This study highlights the applications and developmental trends of dual-modality EEG-fNIRS technology. Specifically, this approach can assist in diagnosing neurological disorders, assessing activation and connectivity within functional brain regions, and evaluating therapeutic neuromodulation in clinical neurology. Overall, multimodal fusion is poised to advance neuroscience research significantly.

Keywords: Electroencephalogram; Functional near-infrared spectroscopy; Bibliometric analysis; CiteSpace; VOSviewer; Nervous system diseases; Brain-computer interface; Hotspot.

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Introduction

Electroencephalography (EEG) is a widely used technique for monitoring brain electrical activity. Advances in high-density EEG systems and advanced statistical methods have significantly enhanced its spatial resolution.[1,2] Evoked potentials obtained from

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EEG are crucial for evaluating the brain's response to sensory stimuli, offering key insights into neurological function. Consequently, EEG plays a pivotal role in diagnosing and monitoring a broad range of neurological disorders.[3,4]

The functional near-infrared spectroscopy (fNIRS) assesses changes in oxyhemoglobin and deoxyhemoglobin concentrations to infer neuronal activity.[5–8] This technique provides valuable insights into functional brain connectivity and activation patterns during cognitive tasks. Its ability to capture cognitive, visual, and auditory signals expands the applicability of brain-computer interfaces (BCIs), particularly benefiting stroke patients through personalized therapeutic interventions.[9] While fNIRS has gained attention for its capacity to measure hemodynamic responses, similar to functional magnetic resonance imaging, it is limited by relatively low spatial and depth resolution.[10,11]

EEG is characterized by high temporal resolution but limited spatial resolution, whereas fNIRS offers better spatial resolution with lower temporal precision. To address these individual limitations, the integration of EEG and fNIRS, often termed photoelectric synchronization, has been applied in research and clinical practices due to their complementary strengths. By combining electrical and hemodynamic data, this multimodal approach offers a more comprehensive understanding of brain function.[12,13] Studies have demonstrated the unique value of EEG-fNIRS integration in exploring functional connectivity during resting and sleep states, investigating the neural mechanisms of emotional interaction, and analyzing complex neural activity patterns during motor execution, observation, and imagery.[14,15] This synergistic approach enables high-resolution analysis of cortical activation patterns, facilitating the detection of subtle brain activity and connectivity features. It has significantly advanced our understanding of the neurophysiological mechanisms underlying motor and neurological disorders, providing robust support for diagnosis and therapeutic interventions. For instance, EEG-fNIRS integration has proven effective in mechanistic studies of mitochondrial epilepsy.[16]

The application of photoelectric synchronization technology extends further—to detecting brain activity in infants and children, assessing residual consciousness in patients with brain injuries, and advancing emotion recognition models in human-computer interaction. These applications highlight the potential of photoelectric synchronization as a frontier in neuroscience and clinical research. Despite its growing relevance, comprehensive evaluations of the progress and future directions in this field remain limited. Bibliometric analysis, a quantitative method for evaluating scientific literature, attempts to identify patterns, trends, and relationships within a body of research. This approach provides valuable insights into the evolution and structure of a particular scientific domain. This bibliometric analysis aimed to comprehensively examine the EEG and fNIRS research literature from 2005 to 2024. By evaluating integrated EEG-fNIRS studies, this work sought to identify emerging research trends, highlight pivotal findings, delineate clinical applications, and provide insights to inform and guide future research directions.

Materials and methods

Data sources and retrieval methods

As of May 13, 2024, a systematic search was conducted in the Web of Science Core Collection (WoSCC) database using the following topic search terms: (EEG OR electroencephalogram OR electroencephalography OR electroencephalograph OR electroencephalograms OR "brain mapping" OR encephalogram OR "brain electric activity mapping" OR "brain electric" OR "cerebral electric" OR "brain electrical" OR "cerebral electrical" OR "brain potentials" OR "electroencephalography brain") AND (fNIRS OR "functional near-infrared spectroscopy" OR "functional near-infrared reflectance spectroscopy"). The search was restricted to articles and reviews published in English. All retrieved records and relevant publications were saved in plain text format (.txt) for subsequent analysis, including detailed reference documentation. To identify eligible studies, the titles and abstracts of all retrieved documents were independently screened by a team of authors. Any discrepancies during the screening process were resolved through discussion and consensus. The search strategy and inclusion criteria were developed based on guidelines and recommendations provided by the China Knowledge Translation Assistant.

Software tools and data visualization

A total of 645 publications related to EEG and fNIRS, published between 2005 and 2024, were analyzed using CiteSpace (version 6.2.R3 (64-bit) Beta Advanced) and VOSviewer (version 1.6.20).[17] The geographic distribution and publication output by country were visualized using Tableau Public Desktop (64-bit-2021-3-3). CiteSpace was employed for collaborative network analyses involving countries, institutions, and authors, as well as for keyword co-occurrence and document co-citation analyses.[18,19] VOSviewer was utilized to perform co-authorship and co-occurrence analyses, leveraging its embedded clustering algorithms to reveal collaboration networks among authors and institutions.[20,21] The tool also facilitated advanced analyses, including the exploration of associations between keywords via co-occurrence analysis and the use of a temporal overlay function to visualize dynamic changes in the network over time.[22,23] Data output from CiteSpace and VOSviewer were exported to Microsoft Excel for further classification, filtering, and refinement. To standardize keywords, synonymous terms were merged, duplicates were removed, and irrelevant entries (e.g., numbers) were excluded to ensure accuracy and consistency in the final analysis. A summary of the literature screening process and analytical workflow is presented in the flowchart (Fig. 1).

Results

General analysis

Based on the established search parameters, a total of 645 publications related to EEG-fNIRS were retrieved from the WoSCC for the period 2005–2024. These works originated from 55 countries or regions across Asia, Europe, and the Americas, involving 307 institutions, 481 authors, and 90 research categories, and were published in 213 journals. Regarding publication numbers, a clear upward trend in global research output is evident, with the annual number of publications increasing from a single paper (0.31%) in 2005 to 97 papers (15.03%) in 2023 (Fig. 2a). Concerning publication and citation trends in EEG and fNIRS literature, the overall pattern shows continuous growth from 2004 to 2023. Notably, the number of publications has increased significantly since 2015, rising from about 100 in 2015 to 228 in 2023, indicating that research activity in this field has intensified annually in recent years. The cumulative number of citations grew exponentially, reaching 23,866 in 2023 (Fig. 2b). This trend

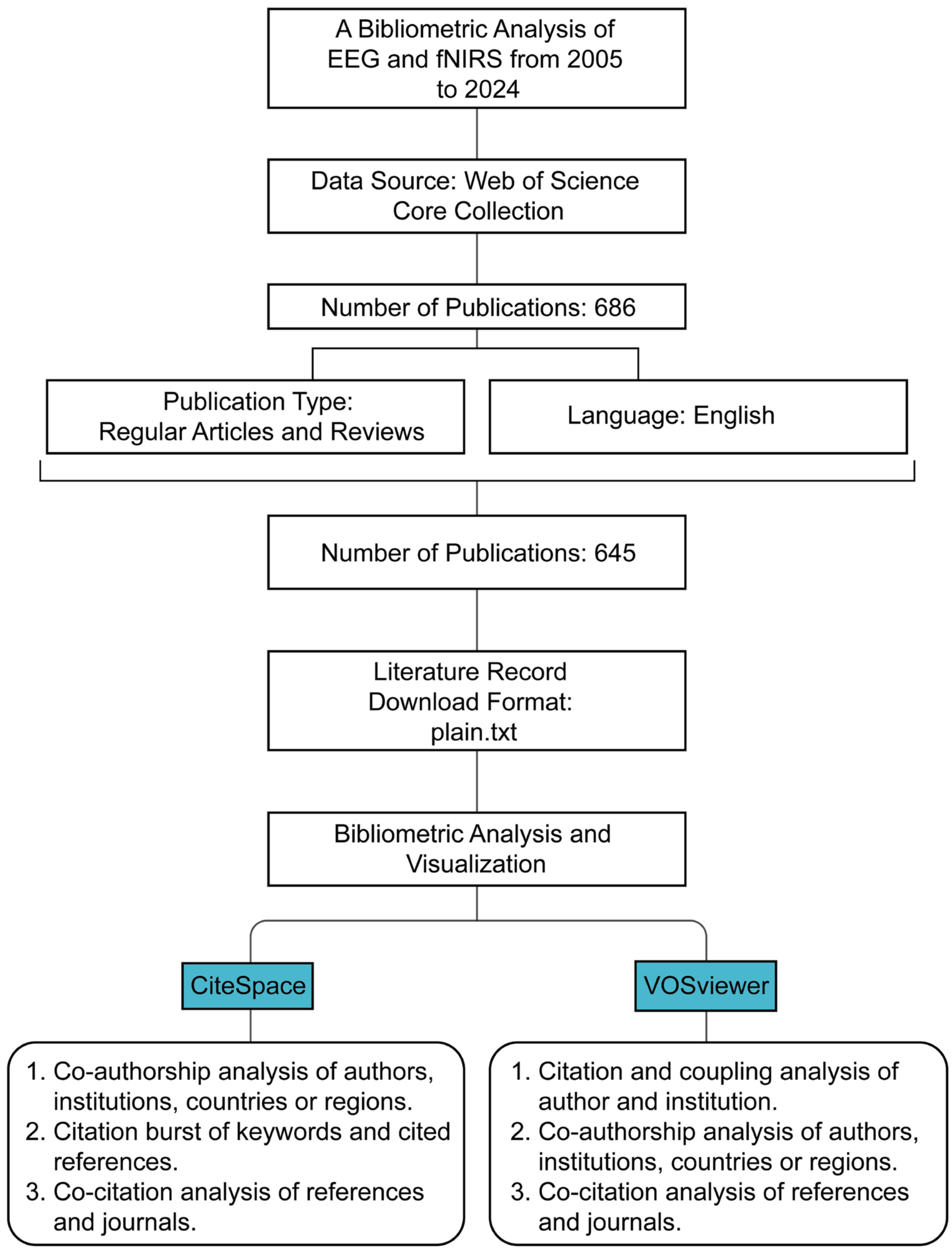

Fig. 1. Flow chart. Illustration of the process of reference inclusion: peer-reviewed articles and reviews published in English. Our initial search retrieved 686 publications, of which 645 m*et al*l eligibility requirements for final analysis. EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy.

signifies growing scholarly interest in EEG-fNIRS research over recent years.

Analysis of publications, citations, and collaborations by countries or regions

We conducted a detailed analysis of contributions from 55 countries or regions engaged in photoelectric synchronization research. Figure 3a depicts a collaboration map, where the size of each circle represents the number of publications from each country or region. The top ten countries by publication count are: the United States in first place with 186 papers (28.84% of the total), followed by China with 139 papers (21.56%), and Germany with 80 papers (12.40%). Other major contributors include Korea (10.39%), Italy (9.61%), the United Kingdom (9.15%), Canada (8.06%), Japan (5.74%), France (4.03%), and Australia (2.95%). Countries ranked 10th and below have published fewer than 20 papers (Table 1). Of particular note is the consistent growth in research output from the United States between 2015 and 2023 (excluding 2018), and the exponential growth from China between 2016 and 2023. In contrast, both Germany and South Korea have experienced stable but declining trends in annual publication numbers since 2017 (Fig. 3b). We analyzed co-authorship among 27 countries that have

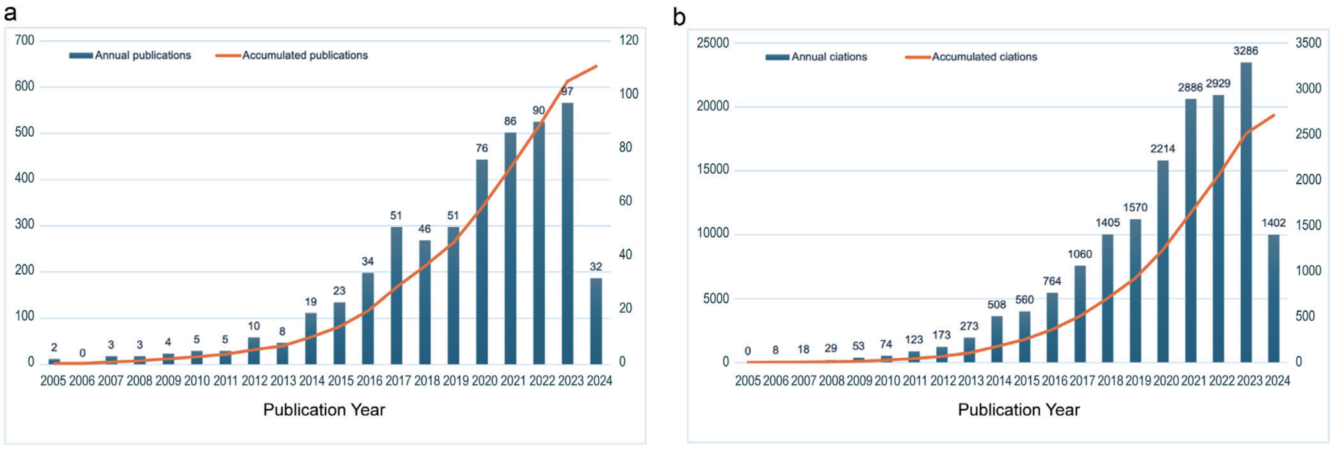

Fig. 2. Distribution of publications from 2005 to 2024. (a) Blue bars: annual publications; yellow curve: accumulated publications. The left axis shows data for accumulated publications, and the right axis shows data for annual publications. (b) Citation trends from 2005 to 2024. Blue bars: number of annual paper citations; yellow curve: cumulative number of paper citations. The left axis shows data on the cumulative number of citations to papers, and the right axis shows data on the annual number of citations to papers.

each published at least five papers in this field. In the collaboration network, node size indicates the number of publications per country, while line thickness reflects the level of cooperation between countries. The top five countries with the strongest overall collaborative strength are the United States (142), Germany (74), China (69), the United Kingdom (50), and Italy (36) (Fig. 3c). In terms of citation count, the United States leads with 6,519 citations, followed by Italy (3,509), Germany (2,930), South Korea (2,712), China (2,115), Japan (2,108), the United Kingdom (1,389), and Canada (1,003) (Table 1). Overall, the relatively low publication output from individual countries and the limited international collaboration suggests significant potential to strengthen partnerships in this field. Enhancing such collaborations could greatly contribute to the development and advancement of EEG-fNIRS research across different nations.

Analysis of institutional output and collaboration

The analysis of institutional collaborations reveals that a total of 307 institutions have contributed to EEG and fNIRS research. The top 10 institutions by publication count and related metrics were analyzed in detail (Table 2). Université de Montréal ranked first with 27 articles (4.19%), followed by the Catholic University of the Sacred Heart (3.26%), Pusan National University (3.10%), Beijing Normal University (2.95%), and the University of London (2.79%). The collaboration network diagram illustrates relationships among these 307 institutions. Each node represents an institution, with node size proportional to the number of publications. Larger nodes indicate higher research output, while node color reflects publication year. Université de Montréal occupies a central position in the network, with the highest number of connections, underscoring its role as a key hub for collaboration. Other high-output institutions, such as the Catholic University of the Sacred Heart, Pusan National University, and Beijing Normal University, also exhibit significant collaborative ties (Fig. 4a). For further analysis, 62 institutions with five or more publications were selected for co-authorship network analysis. The top five institutions by total link strength were Université de Montréal (22), University of Houston (15), McGill University (15), Drexel University (14), and University of Leipzig (14). The diagram demonstrates active international collaboration, particularly among leading universities in Europe, North America, and Asia. For example, Université de Montréal has established close collaborative links with McGill University, University of Houston, and University of London. Notably, these collaborations span multiple regions, highlighting the globalized nature of EEG and fNIRS research (Fig. 4b).

Analysis of author influence and collaboration

Table 3 highlights the top 16 authors and their respective H-indices, ranked by the number of articles they have contributed. Among them, Michela Balconi emerges as the most prolific researcher, with 21 articles, accounting for 3.26% of the total publications. Following closely are Hong Keum-Shik (2.33%), Pouliot Philippe (1.55%), Zhang Yingchun (1.40%), and Rossi Sonja (1.40%), as illustrated in Figure 5a. We analyzed the collaboration network of 50 authors who have co-authored more than five papers (Fig. 5b). The strength of collaboration among authors is indicated by the thickness of the connections between nodes. The authors with the highest total connection strength are Pouliot Philippe (54), Lesage Frederic (50), Vannasing Phetsamone (46), Tremblay Julie (45), and Dang Khoa Nguyen (40).

An author's influence in a scientific field depends more on the number of citations. Coupled network analysis shows that the most cited author in this field is Hong Keum-Shik (1,615 citations), followed by Dan Ippeita (715 citations), Tsuzuki Daisuke (671 citations), Ayaz Hasan (627 citations), and Khan M. Jawad (579 citations) (Fig. 5c). A co-citation network was constructed to analyze intellectual relationships among highly cited authors (Fig. 5d). Six authors exceeded 100 co-citations: ANONYMOUS (149), SCHOLKMANN F (134), HUPPERT T (126), JCUI X (122), FERRARI M (113), and STRANGMAN G (102). Node size corresponds to citation count, while the thickness of connecting lines indicate co-citation frequency, mapping conceptual linkages within the field. Node color represents publication year, with warmer hues denoting more recent work.

Analysis of journals and categories

A total of 645 articles were published across 213 journals. The top 10 journals with the most EEG and fNIRS articles and the top 10 most cited journals are listed in Table 4. Frontiers in Human Neuroscience accounted for the highest number of publications (48

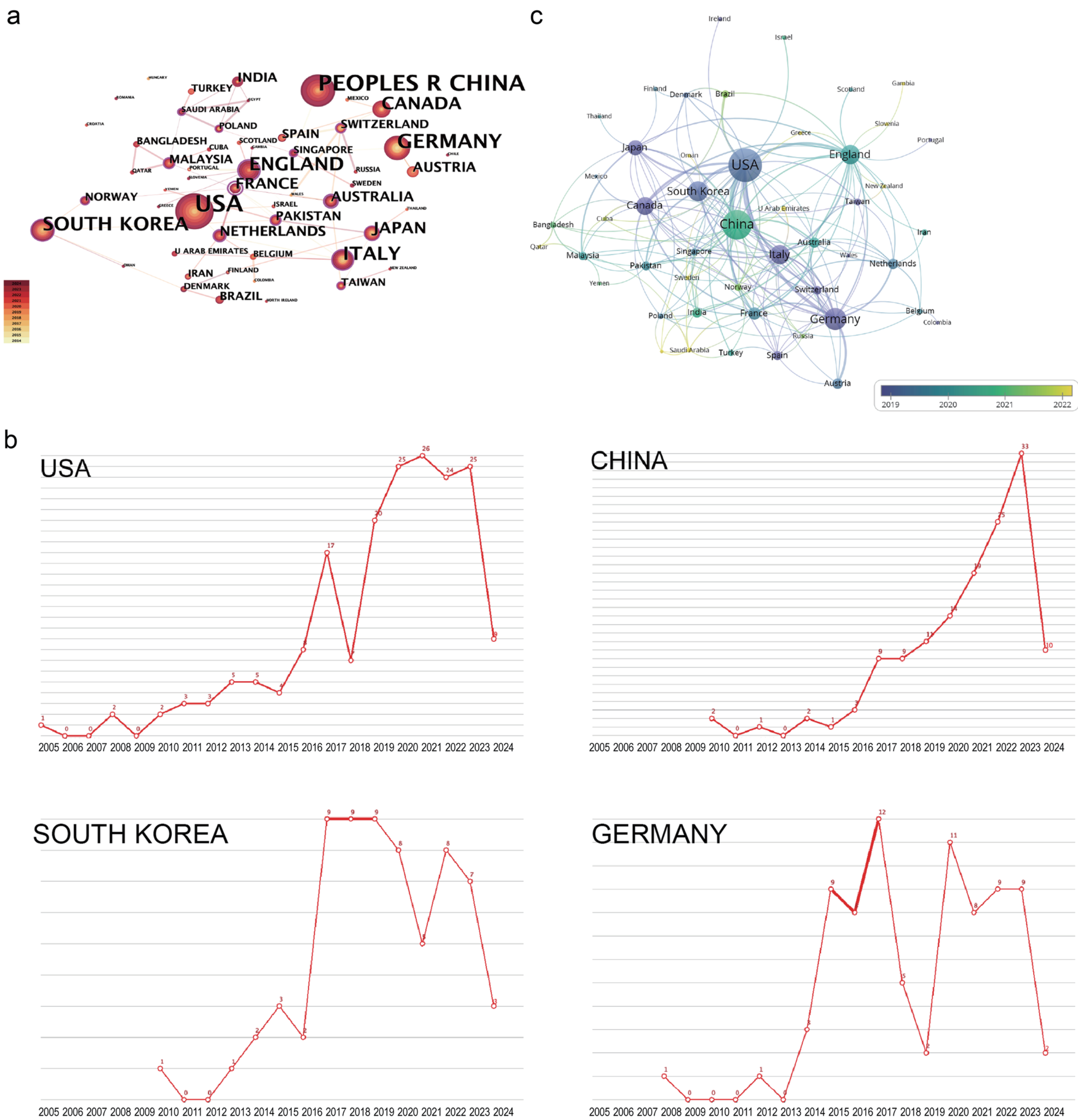

Fig. 3. Countries or regions contributing to EEG and fNIRS research. (a) 55 countries or regions that published articles. (b) Plot showing the change in the trend of articles published in the top four countries. (c) Plot showing the coverage of countries or regions that published more than five papers. The closer the color is to red, the more recent the year of collaboration; the closer the color is to blue, the earlier the year of collaboration. EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy.

articles, 7.44% of all articles), followed by Frontiers in Neuroscience (5.11%), Scientific Reports (4.03%), Neuroimage (3.88%), and IEEE Access (3.88%). In the co-citation analysis, 394 journals were identified as being co-cited in more than 50 publications. Neuroimage had the largest number of citations (595), followed by Front Hum Neurosci (435), PLOS One (394), Hum Brain Mapp (334), and Clin Neurophysiol (307).

A total of 90 research areas are represented in the co-occurrence analysis of Web of Science categories. The most well-represented research area is Neurosciences, comprising 316 records (48.992% of all articles), followed by Biomedical Engineering (74 records, 11.473%), Electrical and Electronic Engineering (70, 10.853%),

Table 1. Top 10 countries or regions in terms of the number of articles

Rank	Countries/Regions	Count (n)	Percentage (%)	Centrality	Year	Total number of citations	Average number of citations	Total link strength
1	USA	186	28.84	0.32	2005	6,519	35.05	142
2	China	139	21.55	0.19	2010	2,115	15.22	69
3	Germany	80	12.40	0.06	2008	2,930	36.63	74
4	South Korea	67	10.39	0.08	2010	2,712	40.48	35
5	Italy	62	9.61	0.07	2009	3,509	56.60	36
6	England	59	9.15	0.46	2008	1,389	23.54	50
7	Canada	52	8.06	0.11	2009	1,003	19.29	35
8	Japan	37	5.74	0.14	2005	2,108	56.97	29
9	France	26	4.03	0.08	2015	893	34.35	35
10	Australia	19	2.95	0.02	2016	369	19.42	19

Psychology (62, 9.612%), and Radiology, Nuclear Medicine, and Medical Imaging (60, 9.302%) (Table 5). This indicates that the EEG-fNIRS dual-modality technique is a multifaceted and multidisciplinary field. Analyzing journals and research areas provides insight into the publications in the field of EEG and fNIRS research, highlighting important journals and major research domains. Researchers can use this information to explore existing literature and identify potential collaboration opportunities.

Analysis of references and bursts in citations

Based on the citation analysis, 106 documents were cited more than 20 times. The collaboration network of these 106 documents is revealed (Fig. 6a). The top ten documents with the highest citation counts are listed in Table 6. Hong *et al*.[24] conducted a review of a framework for brain therapy and BCI for individuals with locked-in syndrome, utilizing a hybrid multimodality approach combining EEG and fNIRS. The integration of multiple modalities in brain imaging and prosthesis control represents a novel advancement in the field.[25] Furthermore, the authors introduced a hybrid EEG-fNIRS scheme aimed at decoding eight distinct brain commands from the frontal brain region for BCI applications.[26]

Using CiteSpace's log-likelihood ratio algorithm, the 10 largest clusters were identified by consensus (Fig. 6b). Based on cluster size (number of documents), the 10 largest clusters are labeled: "information transfer rate", "machine learning", "using functional near-infrared spectroscopy", "human epilepsy", "arithmetic task", "Stroop task", "social interaction", "I social neuroscience", "binge-eating disorder", and "walking intervention". The top-ranked item by citation bursts is Pinti P in Cluster #5.[27] The second is Naseer Noma in Cluster #0,[28] followed by Khan MJ in Cluster #0,[26] Hong KS in Cluster #4,[24] and Buccino AP in Cluster #0 (Fig. 6c).[29]

We utilized VOSviewer to comprehensively analyze all cited references. The co-citation network shown in Figure 6d includes publications with co-citation frequencies exceeding 50. The thickness of connecting lines reflects the strength of co-citation links between references. Among the most frequently cited works, Fazli *et al*.,[30] published in NeuroImage, ranks highest, with a link strength of 972 and a citation frequency of 92. Following closely is the paper by Scholkmann *et al*,[31] also in NeuroImage, with a link strength of 861 and citation frequency of 93. Notably, Ferrari *et al*.,[32] published in NeuroImage, made a significant impact, achieving the highest citation frequency of 103 and a link strength of 806.

Figure 6e illustrates the top 21 most cited references. The dark blue line indicates the citation duration from 2005 to 2024, while the red line indicates the range of mutations in citation duration. The reference with the highest number of citations and citation burst value is the article entitled fNIRS-based BCIs by Noman Naseer, with a

Table 2. The top 10 institutions contributing to publications in EEG and fNIRS

Rank	Institutions	Count (n)	Percentage (%)	Centrality	Year
1	Universite de Montreal	27	4.19	0.1	2011
2	Catholic University of the Sacred Heart	21	3.26	0	2015
3	Pusan National University	20	3.10	0.1	2010
4	Beijing Normal University	19	2.95	0.1	2010
5	University of London	18	2.79	0.1	2008
6	University of Houston	17	2.64	0.08	2013
7	Eberhard Karls University of Tubingen	29	4.50	0.03	2015
8	Harvard University	16	2.48	0.14	2011
9	Drexel University	14	2.17	0.11	2005
10	Polytechnique Montreal	12	1.86	0	2011

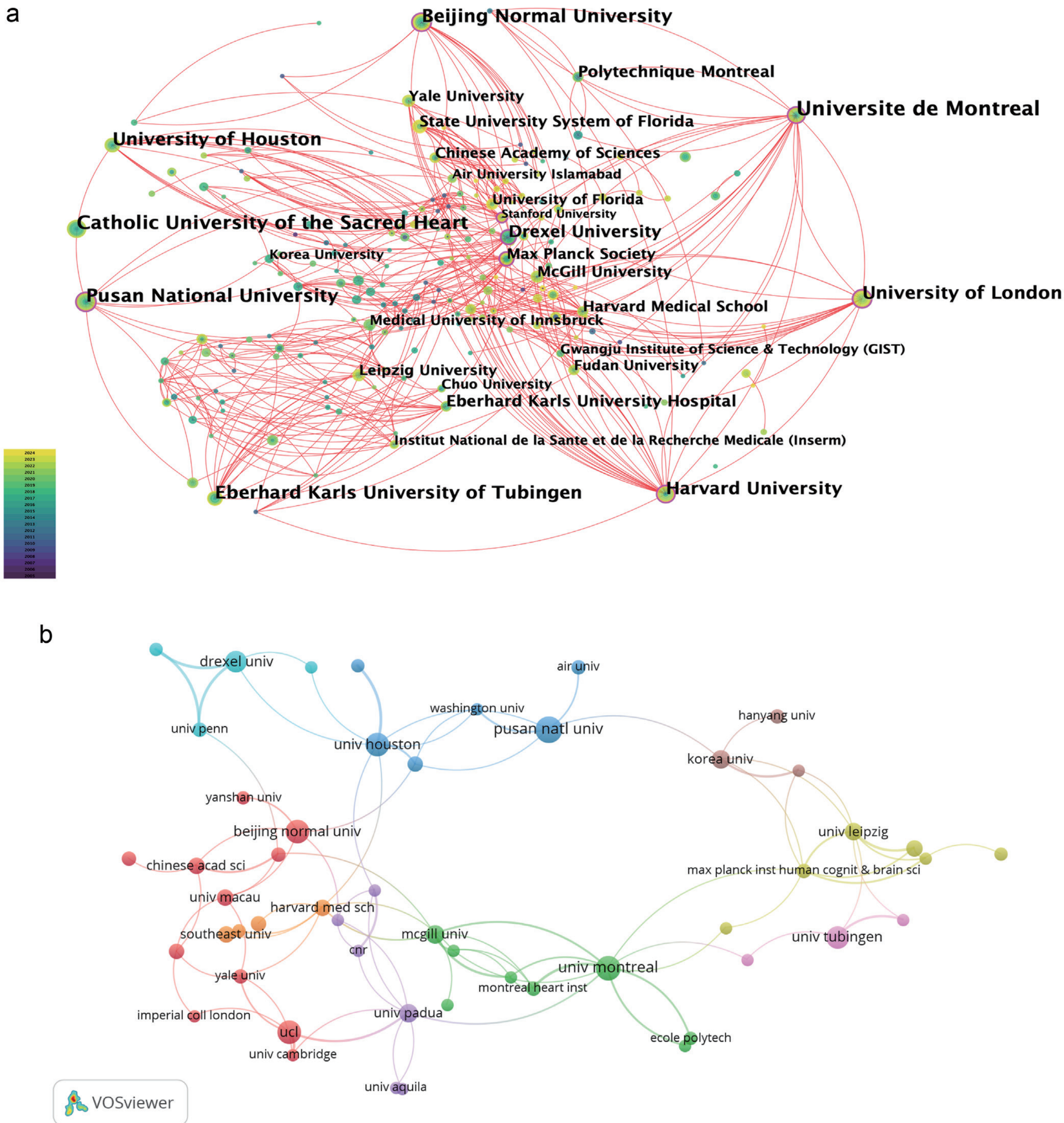

Fig. 4. Institutional contributions to EEG and fNIRS research. (a) Co-occurrence networks of institutions. (b) Network of institutions with ≥ five publications: co-authorship analysis. EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy.

citation burst from 2015 to 2020 of 13.69.[28] The second most cited reference is by Fazli *et al*.,[30] entitled Enhanced performance by a hybrid EEG-fNIRS-BCI, with a citation burst of 13.26.

Analysis of keywords and topics

Figure 7a demonstrates the top 11 keywords with the strongest citation bursts. In total, 538 keywords were collected (Fig. 7b). The five most frequently occurring keywords were: NIRS (239 occurrences), fNIRS (229), EEG (197), functional magnetic resonance imaging (94), and brain (85). A total of 118 author keywords appearing more than five times were analyzed (Fig. 8a). Figure 8b maps these keywords, with colors indicating average publica-

Table 3. Top 16 authors with the most articles about EEG and fNIRS

Rank	Authors	Count	H-index	Institution
1	Balconi, Michela	21	38	Catholic University of the Sacred Heart
2	Hong, Keum-Shik	15	54	Pusan National University
3	Pouliot, Philippe	10	25	Universite de Montreal
4	Zhang, Yingchun	9	15	Guangdong Prov Work Injury Rehabil Hosp
5	Rossi, Sonja	9	13	Medical University of Innsbruck
6	Vanutelli, Maria Elide	9	17	University of Milan
7	Lesage, Frederic	8	45	Polytechnique Montreal
8	Li, Rihui	7	24	University of Macau
9	Ayaz, Hasan	7	37	University of Pennsylvania
10	Lassonde, Maryse	6	53	Universite de Montreal
11	Wallois, Fabrice	6	30	Institut National de la Sante et de la Recherche Medicale
12	Dang Khoa Nguyen	6	20	Universite de Montreal
13	Vannasing, Phetsamone	6	20	Sainte Justine Univ Hosp Ctr
14	Tremblay, Julie	6	17	Sainte Justine Univ Hosp Ctr
15	Al-Shargie, Fares	6	13	Abu Dhabi University
16	Naseer, Noman	6	21	Air University Islamabad

tion years; most keywords were published after 2019, indicated by greener colors. Following clustering of the cited networks, 18 clusters were obtained and labeled with title words or keywords from citing articles (Fig. 8c). Density visualization in Figure 8d shows the same keywords mapped by frequency.

Using CiteSpace's log-likelihood ratio algorithm, the 10 largest clusters were identified by consensus (Fig. 8e). Along the timeline, nodes of different colors indicate references from different years within clusters, while nodes farther to the right indicate more recent references. The modularity Q value (0.9448) was greater than 0.3, and the average silhouette score (0.9605) was greater than 0.7, indicating that the clusters are convincing and well-structured. The five largest clusters were labeled as "motor imagery", "brain mapping", "optical topography", "neurovascular coupling", and "medical signal processing". Examining the timing of keyword appearance allows us to understand the development of these fields over time and estimate recent trends and directions. Figure 8f shows the high-frequency subject word map from 2005 to 2024. The research focus has gradually shifted from disease diagnosis toward treatment research. Attention should be paid to recent hotspots such as "task analysis", "feature extraction", "deep learning", and "coherence".

Discussion

This study conducted a bibliometric analysis of literature extracted from public databases to identify research hotspots and future development directions in EEG and fNIRS. Notably, a significant rise in publication activity has been observed since 2020, likely driven by advances in technologies such as BCI and artificial intelligence, which have positioned EEG-fNIRS as a compelling research topic. Despite growing attention from the scientific community, substantial potential remains for further expansion in this field, particularly in the context of photoelectric synchronization. The observed trends suggest increasing interest, but the current scale of research indicates considerable room for development and broader exploration.

Additionally, we analyzed the authorship of articles published in the WoSCC and found that the USA dominates the application of EEG and fNIRS. Interdisciplinary and international collaborations play a crucial role in advancing synchronous research in photonics. Université de Montréal is the most active institution, focusing its research on applying EEG-fNIRS to stroke and epilepsy monitoring.[33] In particular, it has played an important role in understanding the pathophysiology of temporal lobe epilepsy, revealing complex local and distal oxygenation changes during temporal lobe seizures and the non-linear hemodynamic response in refractory focal epilepsy in humans.[34,35] The University of Montréal exhibits the highest intermediary centrality and connection strength, boasting the strongest connections to other institutions and the highest number of collaborative publications. Following closely are the University of Eberhard Karls in Tübingen, Germany, and Drexel University in the USA, ranked second and third in the collaboration analysis, respectively. Pusan National University, meanwhile, achieved the highest average citation count in this study.

Michela Balconi is the most active researcher in this field. As evidenced by 21 co-authored publications from 2015 to 2024, her research primarily focuses on detecting frontal cortex responses to emotions via EEG and fNIRS under different environmental conditions,[36] such as resting state,[37,38] COVID-19,[39] painful stimuli,[40] audiovisual stimuli,[14] and interoceptive attentiveness.[41,42] Additionally, Balconi *et al*.[43] used EEG and fNIRS to reveal a facilitatory role for motor imagery and executive motion sensation, suggesting that readiness potential amplitude acts as a predictor of hemodynamic brain activity, modulated by task and gesture type factors. Recent research has focused on EEG-fNIRS multimodal hyperscanning techniques in social interactions, including cooperative and competitive relationships,[44–47] as well as interpersonal relationships,[48] highlighting brain network connectivity in neuroscience as a current hotspot and cutting-edge direction for the field.[49] Keum-Shik Hong of Pusan National University, together

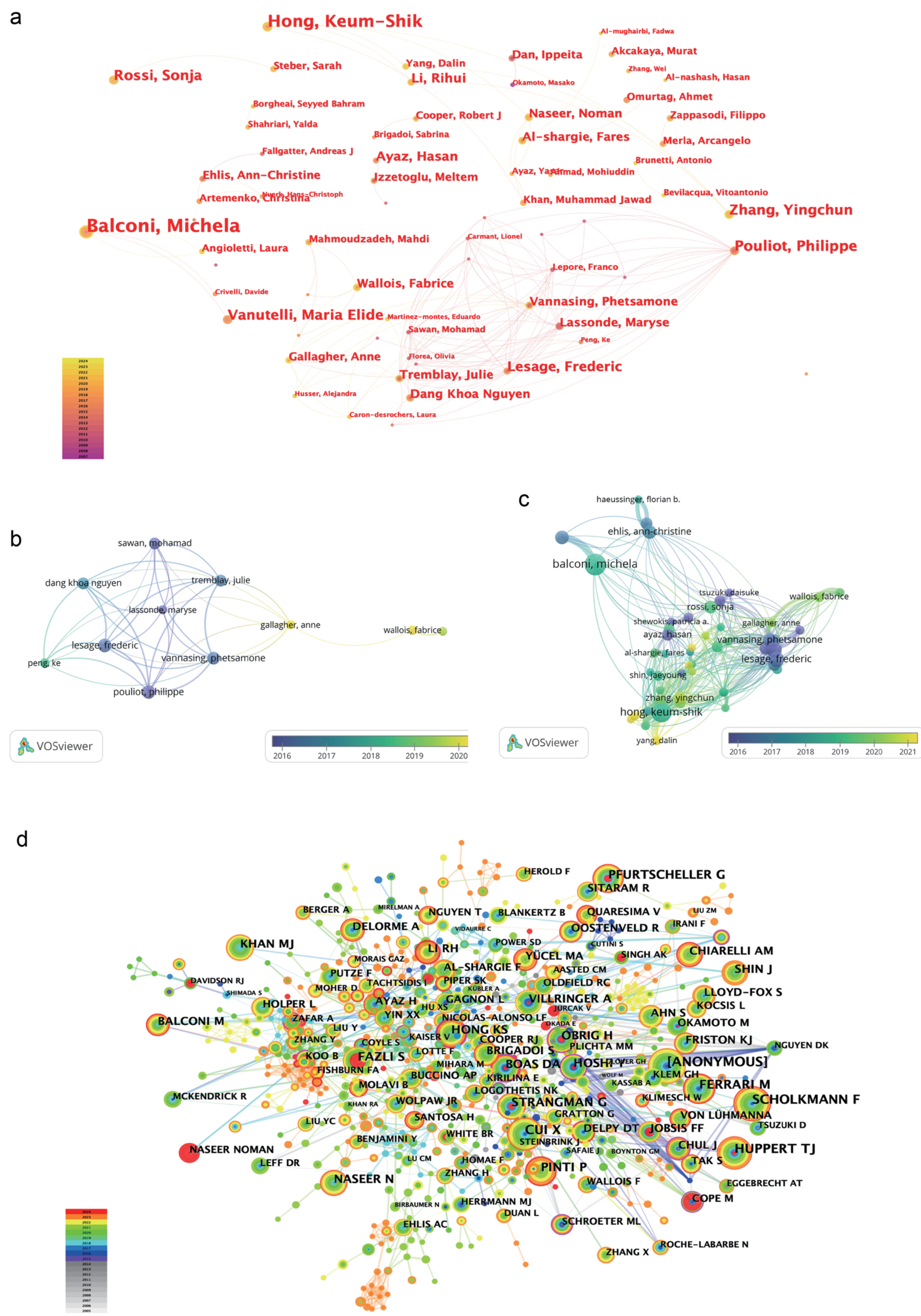

Fig. 5. Authors contributing to EEG and fNIRS research. (a) Author coupling network analysis. (b) Top 10 authors with the largest number of publications. (c) Network map of authors who were co-cited in more than five publications. (d) Author co-citation analysis. Each node represents a cited author, and each link between two nodes represents a co-citation relationship. The size of each node represents the number of citations for that author. EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy.

Table 4. Top 10 popular journals and cited journals

Rank	Popular journals	Records (n)	2024 impact factor	2024 JCR Partition	Cited journals	Cita-tions	2024 impact factor	2024 JCR Partition
1	Frontiers In Human Neuroscience	48	2.9	Q3	Neuroimage	595	5.7	Q1
2	Frontiers In Neuroscience	33	4.3	Q2	Front Hum Neurosci	435	2.9	Q3
3	Scientific Reports	26	4.6	Q2	Plos One	394	3.7	Q2
4	Neuroimage	25	5.7	Q1	Hum Brain Mapp	334	4.8	Q1
5	Ieee Access	25	3.9	Q2	Clin Neurophysiol	307	4.7	Q1
6	Sensors	23	3.9	Q2	Scientific Reports	285	4.6	Q2
7	Neurophotonics	21	5.3	Q1	Front Neurosci-Switz	274	4.3	Q2
8	Brain Sciences	20	3.3	Q3	P Natl Acad Sci Usa	273	11.1	Q1
9	Ieee Transactions On Neural Systems	18	4.9	Q2	J Neurosci Meth	254	3	Q3
10	Plos One	18	3.7	Q2	J Neurosci	248	5.3	Q1

JCR, Journal Citation Reports.

with researchers from the University of Wisconsin-Madison and Sejong University, has made significant contributions to optoelectronic synchronization research from an EEG-fNIRS-BCI perspective.[25,50] Their work involves detecting brain signals during various tasks, assessing activation of specific brain regions, and achieving precise classification of brain signals through multimodal techniques. Research in this area has advanced the development of wearable BCIs.[28,51,52] Philippe Pouliot has also significantly contributed to advancing optoelectronic synchronization research from an EEG-fNIRS-BCI perspective. As a Professor of Neuroscience at the University of Montréal, his primary focus has been on enhancing algorithms for NIRS technology to improve visualization of functional brain connectivity.[53,54]

Clinical applications of EEG-fNIRS

According to keyword and theme analyses, Alzheimer's disease, epilepsy,[55] attention-deficit hyperactivity disorder, stroke,[56] consciousness disorders, and Parkinson's disease are among the most prevalent clinical applications of EEG-fNIRS.[57] The technique was initially used to study cognitive processes such as attention, working memory, target categorization, problem-solving, and human waste processing.[58] In recent years, it has been extensively applied in cognitive neurosciences,[59] neurological disorders,[60] psychiatric disorders,[61] mental health, pediatrics,[62] sociology,[63] and psychology. This section focuses on the use of EEG-fNIRS techniques in clinical disorders.

EEG dynamically monitors brain activity through electrical signals with high temporal resolution, while fNIRS detects cerebral blood oxygenation changes using near-infrared light, offering high spatial resolution. These complementary, non-interfering techniques provide a more comprehensive view of brain function. Jindal *et al*.[64] used fNIRS-EEG integration to study changes in brain activity during stroke recovery. They found that changes in rSO2 were negatively correlated with EEG power changes following electrical stimulation, indicating that decreased EEG power corresponded to increased corticospinal excitability. This study expands the application of fNIRS-EEG in assessing brain activity patterns in stroke patients and provides a quantitative method for evaluating therapeutic interventions.[64] Similarly, Li *et al*.[13] developed a multimodal neuroimaging technique combining EEG and fNIRS to assess motor deficits post-stroke. In their study involving 18 stroke patients and nine healthy controls, they demonstrated reduced task-induced activity in the somatosensory cortex of stroke patients and highlighted how improved functional connectivity in

Table 5. Top 10 well-represented research areas

Rank	Research areas	Record (n)	% (of 654)
1	Neurosciences	316	48.992
2	Engineering biomedical	74	11.473
3	Engineering electrical electronic	70	10.853
4	Psychology	62	9.612
5	Radiology nuclear medicine medical imaging	60	9.302
6	Multidisciplinary sciences	51	7.907
7	Optics	49	7.597
8	Neuroimaging	43	6.667
9	Computer science information systems	38	5.891
10	Instruments instrumentation	35	5.426

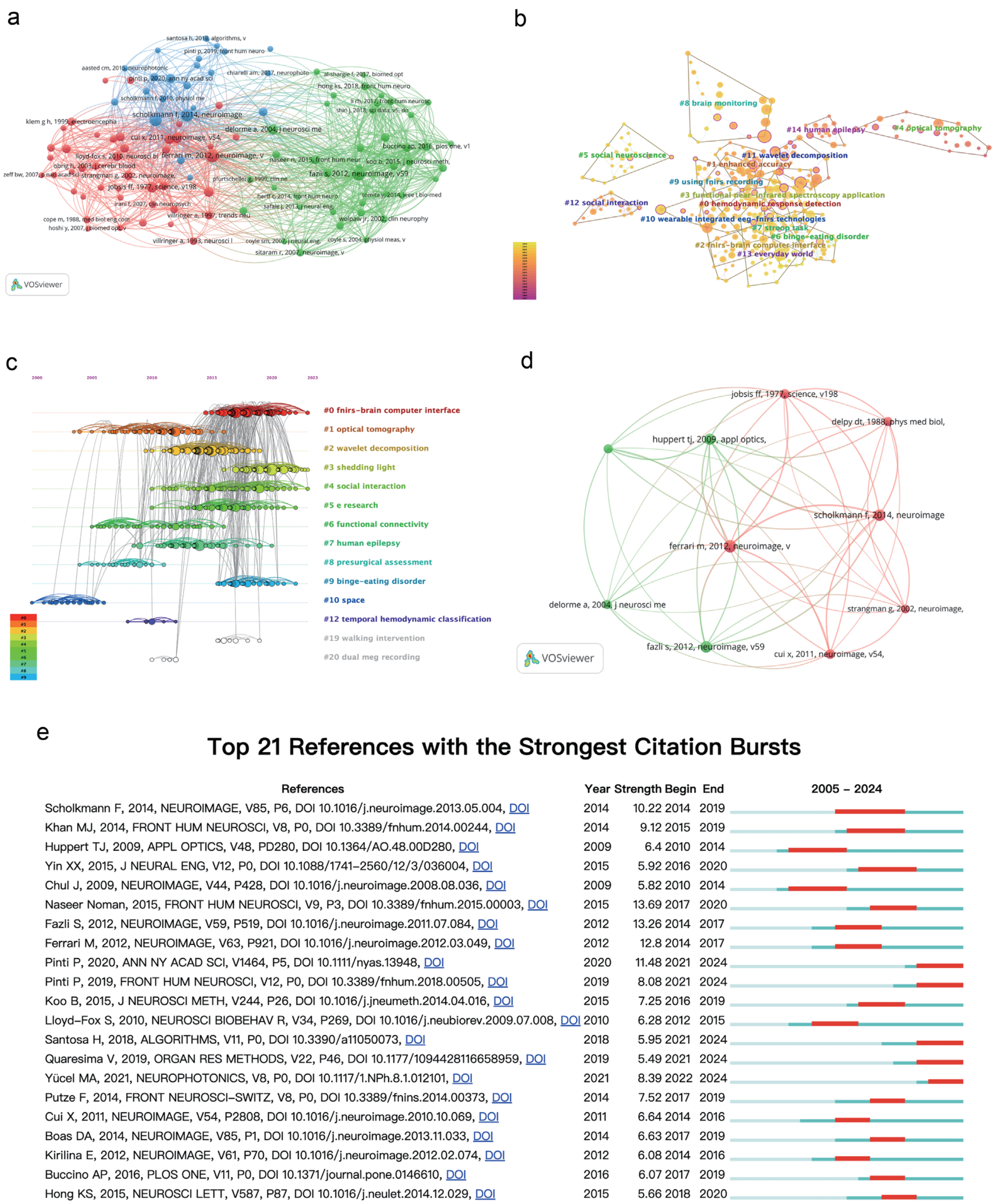

Fig. 6. Citation and co-citation analyses. (a) Network map of documents with more than 20 citations. (b) Literature clustering graph. (c) Literature timeline graph. (d) Network map of documents co-cited in more than 50 publications. (e) The top 21 references with robust citation bursts.

Table 6. Top 10 citation analysis of documents on EEG and fNIRS research

Rank	Title	First author	Corresponding Author	Source	Publication year	Citations (n)
1	Feature extraction and classification methods for hybrid fNIRS-EEG brain-computer interfaces	Hong, KS	Hong, MJ	Frontiers in Human Neuroscience	2018	31
2	Hybrid brain-computer interface techniques for improved classification accuracy and increased number of commands: a review	Hong, KS	Khan, MJ	Frontiers in Neurorobotics	2017	29
3	Hybrid EEG-fNIRS-Based Eight-Command Decoding for BCI: Application to Quadcopter Control	Khan, MJ	Hong, KS	Frontiers in Neurorobotics	2017	21
4	Early detection of hemodynamic responses using EEG: a hybrid EEG-fNIRS study	Khan, MJ	Hong, KS	Frontiers in Human Neuroscience	2018	18
5	A brain-computer interface based on a few-channel EEG-fNIRS bimodal system	Ge, S	Wang, H	IEEE Access	2017	17
6	Hybrid EEG-fNIRS bei fusion using multi-resolution singular value decomposition (MSVD)	Khan, MU	Hasan, MAH	Frontiers in Human Neuroscience	2020	17
7	Enhancing classification performance of fNIRS-BCI by identifying cortically active channels using the z-score method	Nazeer, H	Ayaz, Y	Sensors	2020	16
8	Improvement of information transfer rates using a hybrid EEG-NIRS brain-computer interface with a short trial length: offline and pseudo-online analyses	Shin, J	Hwang, HJ	Sensors	2018	15
9	Enhancing the performance of a hybrid EEG-fNIRS system using channel selection and early temporal features	Li, R	Zhang, Y	Frontiers in Human Neuroscience	2017	15
10	Shining a light on awareness: a review of functional near-infrared spectroscopy for prolonged disorders of consciousness	Rupawala, M	Cruse, D	Frontiers in Neurology	2018	15

EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy.

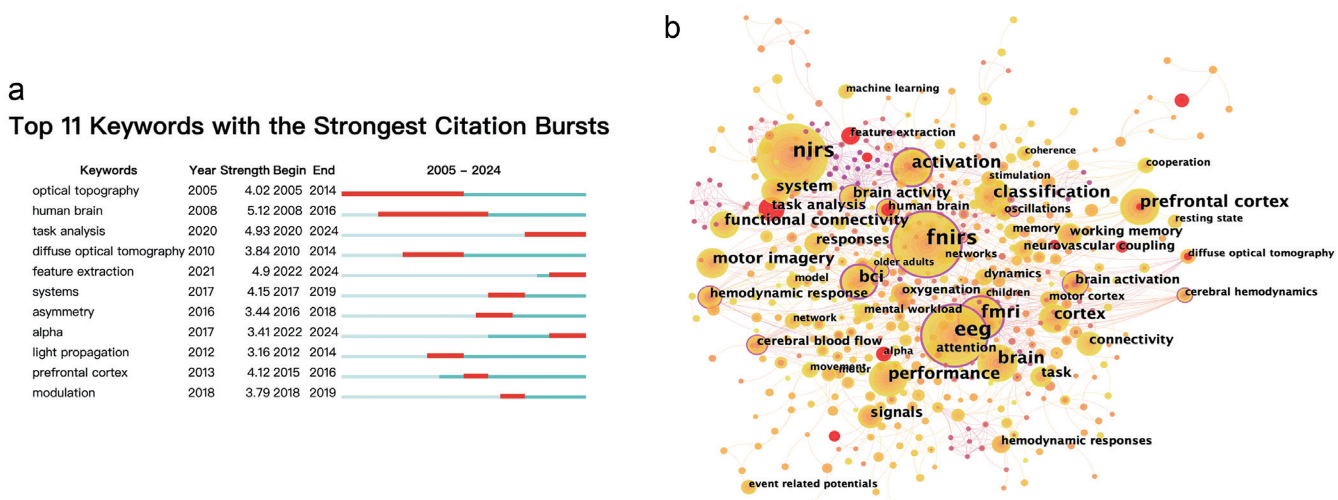

Fig. 7. Keyword co-occurrence and ranking. (a) The top 11 bursts of keywords analyzed by CiteSpace; "strength" represents the intensity of the burst, "begin" represents the starting year of the burst, "end" indicates the ending year of the burst; the red dotted line indicates the duration of the burst. The blue line indicates the entire period from 2005 to 2024. (b) Keywords: co-word network and clustering in the field of EEG and fNIRS. Node size reflects co-word frequency; links represent co-word intensity; different colors represent clustering results of the co-word network; closer relationships share the same color. EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy.

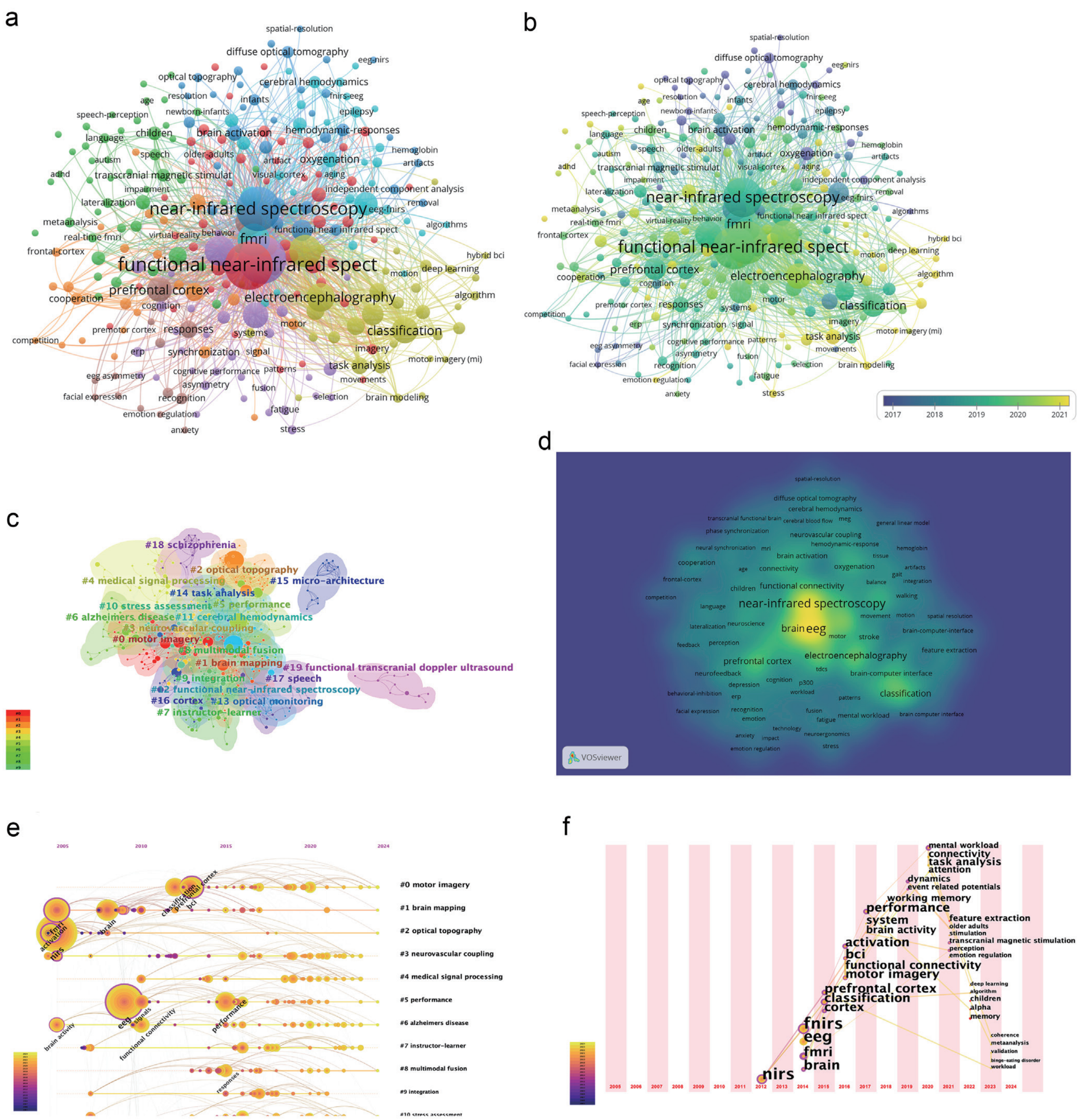

Fig. 8. Co-occurrence analysis of keywords. (a) Mapping of keywords from studies. (b) Distribution of keywords according to average publication year (blue: earlier; red: later). (c) Each node represents a keyword; links between nodes represent co-citation intensity; different colors represent different clusters. (d) Distribution of keywords according to mean frequency of appearance. Keywords in yellow occurred with the highest frequency. (e) The largest 10 clusters. (f) High-frequency topic keywords from 2005 to 2024.

motor-related areas correlated with motor recovery during rehabilitation. Baseline connectivity patterns also predicted recovery outcomes, emphasizing the potential of fNIRS-EEG integration in monitoring and predicting rehabilitation success.[13] Overall, fNIRS-EEG integration leverages the advantages of high temporal and spatial resolution, offering new insights into neurovascular coupling, brain network plasticity, and motor recovery in stroke rehabilitation. This multimodal approach not only enhances understanding of brain activity mechanisms but also promotes precise clinical applications and rehabilitation strategies.

Li and colleagues integrated EEG and fNIRS data with machine learning techniques to enhance the precision of depression diagnosis.[65] They collected resting-state EEG signals and hemodynamic data from the forehead of 25 patients diagnosed with depression and 30 healthy individuals. By leveraging a support vector machine model, they achieved a classification accuracy of 92.7% using hybrid EEG-fNIRS features, compared to 81.8% with EEG data alone. Key biomarkers distinguishing depressive states included enhanced local efficiency in the delta band, hemispheric asymmetry in the theta band, and brain oxygen entropy.[65] These findings underscore the potential of integrating EEG and fNIRS with machine learning as a reliable, non-invasive tool for individual-level depression diagnosis, offering both spatial and temporal insights into underlying neural mechanisms.

The integration of EEG and fNIRS has also shown increasing relevance in epilepsy research. Nourhashemi *et al*.[66] employed this multimodal approach to investigate 25 episodes of childhood absence seizures in eight pediatric patients. Approximately 20 seconds before the onset of spike-wave discharges, transient shifts in direct current potentials were detected, correlating with preictal hemodynamic changes in cerebral blood flow and hemoglobin levels. These findings revealed intricate neurovascular interactions preceding seizures, providing a deeper understanding of mechanisms underlying absence epilepsy.[66] Peng *et al*.[67] further explored the role of EEG-fNIRS integration in epilepsy, focusing on both focal seizures and interictal epileptiform discharges. Their review highlighted the potential of these technologies to evaluate hemodynamic and neuronal changes associated with epileptic events, improving the localization and lateralization of seizure foci, particularly in focal epilepsy. Specific patterns of cerebral blood volume and oxygenation changes were associated with various seizure types, such as temporal and frontal lobe epilepsy. Notably, fNIRS could detect pre-seizure hemodynamic alterations, offering new insights into seizure initiation.[67] Collectively, these studies demonstrate the potential of EEG-fNIRS integration as a robust tool for understanding the neurovascular mechanisms of epilepsy and advancing diagnostic and therapeutic strategies. Future research should prioritize expanding the clinical applicability of this multimodal approach.

Strengths and weaknesses of the study

This research conducted a comprehensive search and analysis of literature encompassing various terms related to EEG and fNIRS. The analysis utilized two distinct econometric software tools, potentially introducing bias due to variations in calculation methods between the software. Given that scalp EEG predominantly captures cortical signals perpendicular to the recording electrodes, while fNIRS detects hemodynamic changes through oxy/deoxyhemoglobin concentration variations to indirectly reflect neural activity, the clinical implementation of EEG-fNIRS integration remains largely confined to research settings. This approach currently offers limited practical utility for clinicians engaged in the non-invasive diagnosis and treatment of brain disorders.

This study represents the first bibliometric analysis to systematically document and evaluate clinically treated EEG and fNIRS. An extensive literature review was conducted, though some limitations exist. Primarily, the search and analysis relied predominantly on the WoSCC core database, neglecting other databases such as PubMed and Scopus, potentially overlooking pertinent literature. Nevertheless, it is important to acknowledge that WoSCC is a widely utilized database in scientometrics, with most bibliometric software compatible with its format. Furthermore, incomplete keyword extraction may have impacted the outcomes of keyword analysis.

Future research directions

Challenges persist in optoelectronic synchronization, including limited spatial resolution and the inability to capture subcortical data. To address these limitations, potential strategies include incorporating supplementary sensors, integrating complementary modalities such as EEG, and augmenting fNIRS optoelectronic probes. Additionally, further optimization of signal processing and algorithms for EEG-fNIRS applications is needed.[5,6,68] A significant additional limitation pertains to the temporal characteristics of the signals. EEG signals exhibit high temporal resolution, enabling analysis of both spectral and temporal dynamics. In contrast, fNIRS signals reflect slower hemodynamic changes, introducing an inherent physiological latency relative to the underlying neural activity.[69,70] Therefore, achieving precise temporal synchronization (neurovascular coupling) between the fast electrical events measured by EEG and the slower hemodynamic responses measured by fNIRS presents a critical methodological challenge.

Wearable, integrated EEG-fNIRS technology represents a critical advancement in this field. Supporting large channel counts, extensive dynamic ranges, and rapid data acquisition and transmission requires enhanced data interfaces and control schemes. Furthermore, dry EEG electrodes with high gain and input impedance may be the optimal choice for extended periodic monitoring.[12] The integration of EEG and fNIRS technologies faces inherent technical limitations. Although commercial devices capable of simultaneous EEG-fNIRS recording are available, achieving spatially co-localized measurements of neuronal activity remains challenging. This difficulty arises primarily from fundamental differences in signal acquisition mechanisms and the physical constraints of the hardware. EEG detects electrical potentials generated by neuronal populations, with relatively small electrodes achieving good contact with the scalp surface.[71] In contrast, fNIRS measures hemodynamic responses by detecting changes in near-infrared light absorption between optical sources (emitters) and detectors (optodes). These optodes possess a finite size and require specific spacing to measure hemodynamic responses within underlying tissue. Consequently, to attempt spatial correspondence (co-channel configuration), EEG electrodes must be placed within the gaps between fNIRS optodes. This placement inevitably compromises spatial coverage and the fidelity of EEG signal acquisition due to physical obstruction and suboptimal electrode positioning. These spatial constraints also hinder comprehensive coverage of the entire brain region with truly co-localized EEG-fNIRS channels.[72]

BCI research frequently utilizes integrated EEG-fNIRS systems to enhance the amount of accessible brain information and improve classification accuracy.[73,74] Non-invasive BCIs have demonstrated potential in stroke rehabilitation and are commonly applied in motor, sensory, and cognitive functions; however, limited spatial resolution remains a recognized constraint.[75] Moreover, the utilization of non-invasive BCIs has been found to augment the quantity of brain-derived information.

Conclusions

Undoubtedly, EEG-fNIRS multimodal technology will become an important imaging technique for disease diagnosis in clinical settings, useful for guiding treatment. The purpose of this study was to provide an overview of global publications using bibliometric methods and visualization tools to uncover changes and developments in the field over recent decades. Optically synchronized multimodal fusion is valuable as a non-invasive, non-implantable examination in clinical BCI applications involving cross-fertilization of multiple disciplines. The Global Brain Initiative, proposed in 2023, outlines future directions in neurology. Cyberneuroscience is a multidisciplinary clinical collaboration that requires further exploration and mastery. Moving forward, research should prioritize examining the human brain, task analysis, feature extraction, and brain-camera interface challenges. It is essential to adopt a multidisciplinary approach and leverage multi-omics technology to facilitate collaboration among research groups across disciplines. Ultimately, the goal is to identify additional prognostic tools for neurological diseases through both clinical and basic research.

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Conflict of interest

The authors declare no conflict of interest. The research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

Study conception, drafting of the manuscript, figure design (NW, JS), literature review (NW, JS, XC, TC), editing (YH, SZ, XC, TC), revision (YH, SZ), providing feedback on clinical implications, data interpretation (QH, YJ), study supervision and guidance, review, and approval of the final version (YY, JZ).

Data sharing statement

All data supporting the findings in this article are available within the article. Researchers can access the data by applying to the Web of Science Core Collection database and the Google Scholar database.

References

[1] Sciaraffa N, Di Flumeri G, Germano D, Giorgi A, Di Florio A, Borghini G, *et al*. Evaluation of a New Lightweight EEG Technology for Translational Applications of Passive Brain-Computer Interfaces. Front Hum Neurosci 2022;16:901387. doi:10.3389/fnhum.2022.901387, PMID:35911603.

[2] Robinson AK, Venkatesh P, Boring MJ, Tarr MJ, Grover P, Behrmann M. Very high density EEG elucidates spatiotemporal aspects of early visual processing. Sci Rep 2017;7(1):16248. doi:10.1038/s41598-017-16377-3, PMID:29176609.

[3] de Tommaso M, Pecoraro C, Sardaro M, Serpino C, Lancioni G, Livrea P. Influence of aesthetic perception on visual event-related potentials. Conscious Cogn 2008;17(3):933–945. doi:10.1016/j.concog.2007.09.003, PMID:17977747.

[4] de Tommaso M, La Rocca M, Quitadamo SG, Ricci K, Tancredi G, Clemente L, *et al*. Central effects of galcanezumab in migraine: a pilot study on Steady State Visual Evoked Potentials and occipital hemodynamic response in migraine patients. J Headache Pain 2022;23(1):52. doi:10.1186/s10194-022-01421-z, PMID:35484504.

[5] Berger A, Horst F, Müller S, Steinberg F, Doppelmayr M. Current State and Future Prospects of EEG and fNIRS in Robot-Assisted Gait Rehabilitation: A Brief Review. Front Hum Neurosci 2019;13:172. doi:10.3389/fnhum.2019.00172, PMID:31231200.

[6] Chen WL, Wagner J, Heugel N, Sugar J, Lee YW, Conant L, *et al*. Functional Near-Infrared Spectroscopy and Its Clinical Application in the Field of Neuroscience: Advances and Future Directions. Front Neurosci 2020;14:724. doi:10.3389/fnins.2020.00724, PMID:32742257.

[7] Boas DA, Elwell CE, Ferrari M, Taga G. Twenty years of functional near-infrared spectroscopy: introduction for the special issue. Neuroimage 2014;85(Pt 1):1–5. doi:10.1016/j.neuroimage.2013.11.033, PMID:24321364.

[8] Wilcox T, Biondi M. fNIRS in the developmental sciences. Wiley Interdiscip Rev Cogn Sci 2015;6(3):263–283. doi:10.1002/wcs.1343, PMID:26263229.

[9] Bishnoi A, Holtzer R, Hernandez ME. Brain Activation Changes While Walking in Adults with and without Neurological Disease: Systematic Review and Meta-Analysis of Functional Near-Infrared Spectroscopy Studies. Brain Sci 2021;11(3):291. doi:10.3390/brainsci11030291, PMID:33652706.

[10] Hoshi Y, Tamura M. Dynamic multichannel near-infrared optical imaging of human brain activity. J Appl Physiol (1985) 1993;75(4):1842–1846. doi:10.1152/jappl.1993.75.4.1842, PMID:8282640.

[11] Chiarelli AM, Zappasodi F, Di Pompeo F, Merla A. Simultaneous functional near-infrared spectroscopy and electroencephalography for monitoring of human brain activity and oxygenation: a review. Neurophotonics 2017;4(4):041411. doi:10.1117/1.NPh.4.4.041411, PMID:28840162.

[12] Uchitel J, Vidal-Rosas EE, Cooper RJ, Zhao H. Wearable, Integrated EEG-fNIRS Technologies: A Review. Sensors (Basel) 2021;21(18):6106. doi:10.3390/s21186106, PMID:34577313.

[13] Li R, Li S, Roh J, Wang C, Zhang Y. Multimodal Neuroimaging Using Concurrent EEG/fNIRS for Poststroke Recovery Assessment: An Exploratory Study. Neurorehabil Neural Repair 2020;34(12):1099–1110. doi:10.1177/1545968320969937, PMID:33190571.

[14] Balconi M, Vanutelli ME. Hemodynamic (fNIRS) and EEG (N200) correlates of emotional inter-species interactions modulated by visual and auditory stimulation. Sci Rep 2016;6:23083. doi:10.1038/srep23083, PMID:26976052.

[15] Su WC, Dashtestani H, Miguel HO, Condy E, Buckley A, Park S, *et al*. Simultaneous multimodal fNIRS-EEG recordings reveal new insights in neural activity during motor execution, observation, and imagery. Sci Rep 2023;13(1):5151. doi:10.1038/s41598-023-31609-5, PMID:36991003.

[16] Khaksari K, Chen WL, Chanvanichtrakool M, Taylor A, Kotla R, Gropman AL. Applications of near-infrared spectroscopy in epilepsy, with a focus on mitochondrial disorders. Neurotherapeutics 2024;21(1):e00323. doi:10.1016/j.neurot.2024.e00323, PMID:38244258.

[17] Synnestvedt MB, Chen C, Holmes JH. CiteSpace II: visualization and knowledge discovery in bibliographic databases. AMIA Annu Symp Proc 2005;2005:724–728. PMID:16779135.

[18] Braam RR, Moed HF, van Raan AF. Mapping of science by combined co-citation and word analysis. II: Dynamical aspects. J Am Soc Inf Sci 1991;42(4):252–266. doi:10.1002/(SICI)1097-4571(199105)42:4%3C252::AID-ASI2%3E3.0.CO;2-G.

[19] Chen C, Song M. Visualizing a field of research: A methodology of systematic scientometric reviews. PLoS One 2019;14(10):e0223994. doi:10.1371/journal.pone.0223994, PMID:31671124.

[20] van Eck NJ, Waltman L. Citation-based clustering of publications using

CitNetExplorer and VOSviewer. Scientometrics 2017;111(2):1053–1070. doi:10.1007/s11192-017-2300-7, PMID:28490825.

[21] Ding Y, Rousseau R, Wolfram D. Measuring scholarly impact. Methods and Practice. Cham: Springer; 2014. doi:10.1007/978-3-319-10377-8.

[22] Lee P-C, Su H-N. Investigating the structure of regional innovation system research through keyword co-occurrence and social network analysis. Innovation 2010;12(1):26–40. doi:10.5172/impp.12.1.26.

[23] Bordons M, Aparicio J, González-Albo B, Díaz-Faes AA. The relationship between the research performance of scientists and their position in co-authorship networks in three fields. J Informetr 2015;9(1):135–144. doi:10.1016/j.joi.2014.12.001.

[24] Hong KS, Khan MJ, Hong MJ. Feature Extraction and Classification Methods for Hybrid fNIRS-EEG Brain-Computer Interfaces. Front Hum Neurosci 2018;12:246. doi:10.3389/fnhum.2018.00246, PMID:30002623.

[25] Hong KS, Khan MJ. Hybrid Brain-Computer Interface Techniques for Improved Classification Accuracy and Increased Number of Commands: A Review. Front Neurorobot 2017;11:35. doi:10.3389/fnbot.2017.00035, PMID:28790910.

[26] Khan MJ, Hong KS. Hybrid EEG-fNIRS-Based Eight-Command Decoding for BCI: Application to Quadcopter Control. Front Neurorobot 2017;11:6. doi:10.3389/fnbot.2017.00006, PMID:28261084.

[27] Pinti P, Tachtsidis I, Hamilton A, Hirsch J, Aichelburg C, Gilbert S, *et al*. The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience. Ann N Y Acad Sci 2020;1464(1):5–29. doi:10.1111/nyas.13948, PMID:30085354.

[28] Naseer N, Hong KS. fNIRS-based brain-computer interfaces: a review. Front Hum Neurosci 2015;9:3. doi:10.3389/fnhum.2015.00003, PMID:25674060.

[29] Buccino AP, Keles HO, Omurtag A. Hybrid EEG-fNIRS Asynchronous Brain-Computer Interface for Multiple Motor Tasks. PLoS One 2016;11(1):e0146610. doi:10.1371/journal.pone.0146610, PMID:26730580.

[30] Fazli S, Mehnert J, Steinbrink J, Curio G, Villringer A, Müller KR, *et al*. Enhanced performance by a hybrid NIRS-EEG brain computer interface. Neuroimage 2012;59(1):519–529. doi:10.1016/j.neuroimage.2011.07.084, PMID:21840399.

[31] Scholkmann F, Kleiser S, Metz AJ, Zimmermann R, Mata Pavia J, Wolf U, *et al*. A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. Neuroimage 2014;85(Pt 1):6–27. doi:10.1016/j.neuroimage.2013.05.004, PMID:23684868.

[32] Ferrari M, Quaresima V. A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. Neuroimage 2012;63(2):921–935. doi:10.1016/j.neuroimage.2012.03.049, PMID:22510258.

[33] Lareau E, Lesage F, Pouliot P, Nguyen D, Le Lan J, Sawan M. Multichannel wearable system dedicated for simultaneous electroencephalography/near-infrared spectroscopy real-time data acquisitions. J Biomed Opt 2011;16(9):096014. doi:10.1117/1.3625575, PMID:21950928.

[34] Nguyen DK, Tremblay J, Pouliot P, Vannasing P, Florea O, Carmant L, *et al*. Non-invasive continuous EEG-fNIRS recording of temporal lobe seizures. Epilepsy Res 2012;99(1-2):112–126. doi:10.1016/j.eplepsyres.2011.10.035, PMID:22100148.

[35] Pouliot P, Tremblay J, Robert M, Vannasing P, Lepore F, Lassonde M, *et al*. Nonlinear hemodynamic responses in human epilepsy: a multimodal analysis with fNIRS-EEG and fMRI-EEG. J Neurosci Methods 2012;204(2):326–340. doi:10.1016/j.jneumeth.2011.11.016, PMID:22138633.

[36] Balconi M, Grippa E, Vanutelli ME. What hemodynamic (fNIRS), electrophysiological (EEG) and autonomic integrated measures can tell us about emotional processing. Brain Cogn 2015;95:67–76. doi:10.1016/j.bandc.2015.02.001, PMID:25721430.

[37] Balconi M, Grippa E, Vanutelli ME. Resting lateralized activity predicts the cortical response and appraisal of emotions: an fNIRS study. Soc Cogn Affect Neurosci 2015;10(12):1607–1614. doi:10.1093/scan/nsv041, PMID:25862673.

[38] Balconi M, Vanutelli ME, Grippa E. Resting state and personality component (BIS/BAS) predict the brain activity (EEG and fNIRS measure) in response to emotional cues. Brain Behav 2017;7(5):e00686. doi:10.1002/brb3.686, PMID:28523228.

[39] Sansone M, Balconi M. ADV at the Time of COVID-19 Brain Effect between Emotional Engagement and Purchase Intention. Brain Sci 2022;12(5):593. doi:10.3390/brainsci12050593, PMID:35624980.

[40] Balconi M, Angioletti L. Aching face and hand: the interoceptive attentiveness and social context in relation to empathy for pain. J Integr Neurosci 2022;21(1):34. doi:10.31083/j.jin2101034, PMID:35164470.

[41] Balconi M, Angioletti L. Interoceptive Attentiveness Induces Significantly More PFC Activation during a Synchronized Linguistic Task Compared to a Motor Task as Revealed by Functional Near-Infrared Spectroscopy. Brain Sci 2022;12(3):301. doi:10.3390/brainsci12030301, PMID:35326258.

[42] Angioletti L, Balconi M. The Increasing Effect of Interoception on Brain Frontal Responsiveness During a Socially Framed Motor Synchronization Task. Front Hum Neurosci 2022;16:834619. doi:10.3389/fnhum.2022.834619, PMID:35669205.

[43] Balconi M, Cortesi L, Crivelli D. Motor planning and performance in transitive and intransitive gesture execution and imagination: Does EEG (RP) activity predict hemodynamic (fNIRS) response? Neurosci Lett 2017;648:59–65. doi:10.1016/j.neulet.2017.03.049, PMID:28373091.

[44] Balconi M, Vanutelli ME. Cooperation and Competition with Hyperscanning Methods: Review and Future Application to Emotion Domain. Front Comput Neurosci 2017;11:86. doi:10.3389/fncom.2017.00086, PMID:29033810.

[45] Balconi M, Crivelli D, Vanutelli ME. Why to cooperate is better than to compete: brain and personality components. BMC Neurosci 2017;18(1):68. doi:10.1186/s12868-017-0386-8, PMID:28931376.

[46] Balconi M, Vanutelli ME. Functional EEG connectivity during competition. BMC Neurosci 2018;19(1):63. doi:10.1186/s12868-018-0464-6, PMID:30336786.

[47] Balconi M, Gatti L, Vanutelli ME. When cooperation goes wrong: brain and behavioural correlates of ineffective joint strategies in dyads. Int J Neurosci 2018;128(2):155–166. doi:10.1080/00207454.2017.1379519, PMID:28914554.

[48] Balconi M, Fronda G, Vanutelli ME. A gift for gratitude and cooperative behavior: brain and cognitive effects. Soc Cogn Affect Neurosci 2019;14(12):1317–1327. doi:10.1093/scan/nsaa003, PMID:31993657.

[49] Balconi M, Vandelli GV, Angioletti L. Be Creative to Innovate! EEG Correlates of Group Decision-Making in Managers. Sustainability 2024;16(5):2175. doi:10.3390/su16052175.

[50] Hong KS, Naseer N, Kim YH. Classification of prefrontal and motor cortex signals for three-class fNIRS-BCI. Neurosci Lett 2015;587:87–92. doi:10.1016/j.neulet.2014.12.029, PMID:25529197.

[51] Naseer N, Hong KS. Classification of functional near-infrared spectroscopy signals corresponding to the right- and left-wrist motor imagery for development of a brain-computer interface. Neurosci Lett 2013;553:84–89. doi:10.1016/j.neulet.2013.08.021, PMID:23973334.

[52] Khan MJ, Hong MJ, Hong KS. Decoding of four movement directions using hybrid NIRS-EEG brain-computer interface. Front Hum Neurosci 2014;8:244. doi:10.3389/fnhum.2014.00244, PMID:24808844.

[53] Tremblay J, Martínez-Montes E, Hüsser A, Caron-Desrochers L, Lepage C, Pouliot P, *et al*. LIONirs: flexible Matlab toolbox for fNIRS data analysis. J Neurosci Methods 2022;370:109487. doi:10.1016/j.jneumeth.2022.109487, PMID:35090901.

[54] Daneault V, Orban P, Martin N, Dansereau C, Godbout J, Pouliot P, *et al*. Cerebral functional networks during sleep in young and older individuals. Sci Rep 2021;11(1):4905. doi:10.1038/s41598-021-84417-0, PMID:33649377.

[55] Guo Y, Lin Z, Fan Z, Tian X. Epileptic brain network mechanisms and neuroimaging techniques for the brain network. Neural Regen Res 2024;19(12):2637–2648. doi:10.4103/1673-5374.391307, PMID:38595282.

[56] Saway BF, Palmer C, Hughes C, Triano M, Suresh RE, Gilmore J, *et al*. The evolution of neuromodulation for chronic stroke: From neuroplasticity mechanisms to brain-computer interfaces. Neurotherapeutics 2024;21(3):e00337. doi:10.1016/j.neurot.2024.e00337, PMID:38377638.

[57] Abtahi M, Bahram Borgheai S, Jafari R, Constant N, Diouf R, Shahriari Y, *et al*. Merging fNIRS-EEG Brain Monitoring and Body Motion Capture to Distinguish Parkinsons Disease. IEEE Trans Neural Syst Rehabil Eng 2020;28(6):1246–1253. doi:10.1109/TNSRE.2020.2987888, PMID:32305929.

[58] Izzetoglu M, Izzetoglu K, Bunce S, Ayaz H, Devaraj A, Onaral B, *et al*. Functional near-infrared neuroimaging. IEEE Trans Neural Syst Rehabil Eng 2005;13(2):153–159. doi:10.1109/TNSRE.2005.847377, PMID:16003893.

[59] Ji X, Bao B, Li LZ, Pu J, Lin Y, Zhang X, *et al*. EEG and fNIRS datasets based on Stroop task during two weeks of high-altitude exposure in new immigrants. Sci Data 2024;11(1):350. doi:10.1038/s41597-024-03200-8, PMID:38589476.

[60] Othman MH, Bhattacharya M, Møller K, Kjeldsen S, Grand J, Kjaergaard J, *et al*. Resting-State NIRS-EEG in Unresponsive Patients with Acute Brain Injury: A Proof-of-Concept Study. Neurocrit Care 2021;34(1):31–44. doi:10.1007/s12028-020-00971-x, PMID:32333214.

[61] Schneider S, Wagels L, Haeussinger FB, Fallgatter AJ, Ehlis AC, Rapp AM. Haemodynamic and electrophysiological markers of pragmatic language comprehension in schizophrenia. World J Biol Psychiatry 2015;16(6):398–410. doi:10.3109/15622975.2015.1019359, PMID:25816925.

[62] Uchitel J, Vanhatalo S, Austin T. Early development of sleep and brain functional connectivity in term-born and preterm infants. Pediatr Res 2022;91(4):771–786. doi:10.1038/s41390-021-01497-4, PMID:33859364.

[63] Li T, Liu P, Gao Y, Ji X, Lin Y. Advancements in Fatigue Detection: Integrating fNIRS and Non-Voluntary Attention Brain Function Experiments. Sensors (Basel) 2024;24(10):3175. doi:10.3390/s24103175, PMID:38794028.

[64] Jindal U, Sood M, Chowdhury SR, Das A, Kondziella D, Dutta A. Corticospinal excitability changes to anodal tDCS elucidated with NIRS-EEG joint-imaging: An ischemic stroke study. Annu Int Conf IEEE Eng Med Biol Soc 2015;2015:3399–3402. doi:10.1109/EMBC.2015.7319122, PMID:26737022.

[65] Yi L, Xie G, Li Z, Li X, Zhang Y, Wu K, *et al*. Automatic depression diagnosis through hybrid EEG and near-infrared spectroscopy features using support vector machine. Front Neurosci 2023;17:1205931. doi:10.3389/fnins.2023.1205931, PMID:37694121.

[66] Nourhashemi M, Mahmoudzadeh M, Heberle C, Wallois F. Preictal neuronal and vascular activity precedes the onset of childhood absence seizure: direct current potential shifts and their correlation with hemodynamic activity. Neurophotonics 2023;10(2):025005. doi:10.1117/1.NPh.10.2.025005, PMID:37114185.

[67] Peng K, Pouliot P, Lesage F, Nguyen DK. Multichannel continuous electroencephalography-functional near-infrared spectroscopy recording of focal seizures and interictal epileptiform discharges in human epilepsy: a review. Neurophotonics 2016;3(3):031402. doi:10.1117/1.NPh.3.3.031402, PMID:26958576.

[68] von Luhmann A, Muller KR. Why build an integrated EEG-NIRS? About the advantages of hybrid bio-acquisition hardware. Annu Int Conf IEEE Eng Med Biol Soc 2017;2017:4475–4478. doi:10.1109/EMBC.2017.8037850, PMID:29060891.

[69] Liao CH, Worsley KJ, Poline JB, Aston JA, Duncan GH, Evans AC. Estimating the delay of the fMRI response. Neuroimage 2002;16(3 Pt 1):593–606. doi:10.1006/nimg.2002.1096, PMID:12169246.

[70] Buxton RB, Uludağ K, Dubowitz DJ, Liu TT. Modeling the hemodynamic response to brain activation. Neuroimage 2004;23(Suppl 1):S220–S233. doi:10.1016/j.neuroimage.2004.07.013, PMID:15501093.

[71] van den Broek SP, Reinders F, Donderwinkel M, Peters MJ. Volume conduction effects in EEG and MEG. Electroencephalogr Clin Neurophysiol 1998;106(6):522–534. doi:10.1016/s0013-4694(97)00147-8, PMID:9741752.

[72] Yeung MK, Chu VW. Viewing neurovascular coupling through the lens of combined EEG-fNIRS: A systematic review of current methods. Psychophysiology 2022;59(6):e14054. doi:10.1111/psyp.14054, PMID:35357703.

[73] Yin X, Xu B, Jiang C, Fu Y, Wang Z, Li H, *et al*. A hybrid BCI based on EEG and fNIRS signals improves the performance of decoding motor imagery of both force and speed of hand clenching. J Neural Eng 2015;12(3):036004. doi:10.1088/1741-2560/12/3/036004, PMID:25834118.

[74] Kaiser V, Bauernfeind G, Kreilinger A, Kaufmann T, Kübler A, Neuper C, *et al*. Cortical effects of user training in a motor imagery based brain-computer interface measured by fNIRS and EEG. Neuroimage 2014;85(Pt 1):432–444. doi:10.1016/j.neuroimage.2013.04.097, PMID:23651839.

[75] Hughes C, Herrera A, Gaunt R, Collinger J. Bidirectional brain-computer interfaces. Handb Clin Neurol 2020;168:163–181. doi:10.1016/B978-0-444-63934-9.00013-5, PMID:32164851.