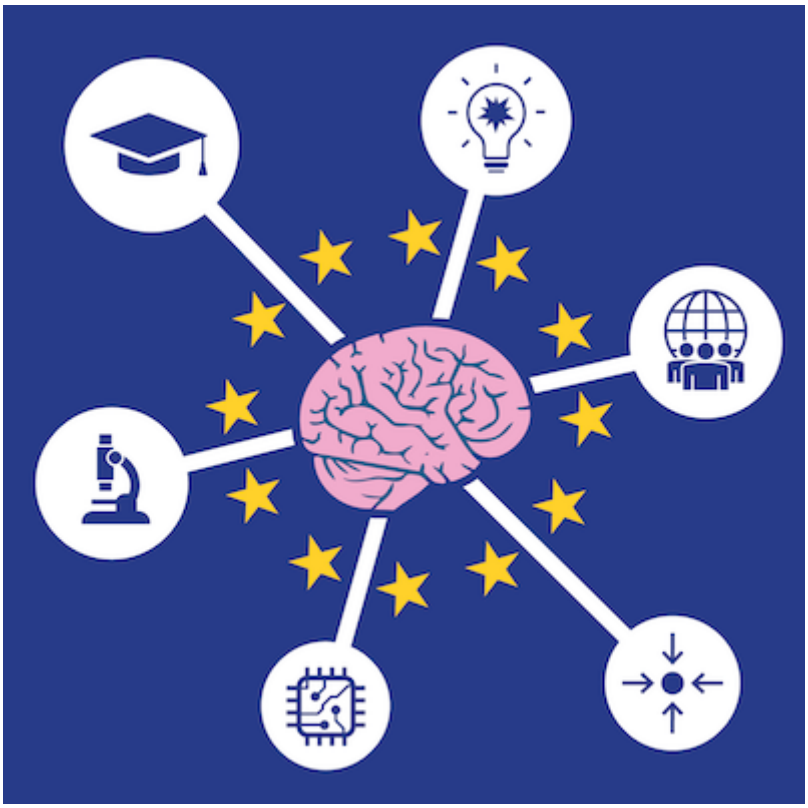
Neurotech^{EU}

The European University of Brain and Technology



[D5.2]
[Short term technological innovation targets]

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Introduction

The deliverable D5.2 was defined as follows: The participants bring together regional facts regarding key neurological disorders with major medical, economical and societal impact, state of the art and drawbacks of diagnostic techniques, innovational methodologies for better diagnosis and treatment and determine broader European demands for neurotechnology. In order to objectively assess the state of the art in neurotechnology field and to identify the most prominent challenges that include neurological disorders as well as numerous others with medical, economical and societal impact and in order to characterize the technologies that are utilized globally to provide solutions a detailed bibliometric analysis was conducted. The report below presents the methodological approach and the outcomes of that analysis, which was presented in NeurotechEU Technological and Societal Innovation Summit 2023 to inform Round Table Discussions, which aims at serving for the process of development of short-term technological innovation targets for the NeurotechEU consortium.

Bibliometric analysis methodology implemented

In this section, the methodology for the bibliometric analyses conducted is described. Note that NeurotechEU defined 8 neurotechnology dimensions, which are:

D1 - Empirical and clinical neuroscience
D2 - Theoretical neuroscience
D3 - Neuromorphic computing
D4 - Neuromorphic control/neurorobotics
D5 - Neuroinformatics
D6 - Neuroprosthetics
D7 - Clinical neurotechnology
D8 - Neurometaphysics

The aim of the bibliometric analysis is to reveal the state-of-the art in neurotechnology research in the dimensions of neurotechnology in terms of challenges and technologies where the latter provide solutions to the former. To achieve this, we start with an initial list of terms/themes related to each dimension. These lists are then finalized (and then referred to as **Keywords Utilized**) on the basis of the suggestions of domain experts, an example to which can be seen below. We would like to mention that the abbreviations in the parentheses are not used in the queries, they are only provided to highlight a well-known system/method.

D4 - Neuromorphic control/neurorobotics initial set of keywords utilized: biomechanics, muscle mechanics, musculoskeletal, joint movement, gait analysis, electromyography, sensors, sensor systems, multisensory integration, robotics, powered prostheses, exoskeletons, power, battery, personalized diagnosis, artificial neural networks, artificial intelligence, machine learning, algorithms, controllers, bioelectronics, wearables, wireless communication, nanotechnology, neurofeedback, neurorehabilitation, neuromodulation, amputation, tactile processing, sense of touch, intelligent navigation, robotic mobility, autonomous vehicles, autonomous vehicle interaction, robot learning, stroke, cerebral palsy, spasticity, multiple sclerosis, Parkinson's disease, autism, prostetics, virtual reality, electroencephalography (EEG), electrospinography (ESG), neurostimulation, brain-machine interface (BMI), brain-computer interface (BCI), transcranial Electrical Stimulation (tES), transcranial Direct Current Stimulation (tDCS), transcranial Alternating Current Stimulation (tACS), transcranial Random Noise Stimulation (tRNS), non-invasive brain stimulation (NIBS), transcranial magnetic stimulation (TMS)

The second step of the bibliometric analysis consists of searching the Scopus database for each dimension using queries to obtain journal articles, reviews, and conference papers that

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contain the terms in their title, abstract, or author-defined keywords. The reason why we prefer the Scopus database over Web of Science is the larger number of indexed journals. One of the disadvantages of Scopus is that even though it is possible to run the search queries for an extended number of periods such as five years, which may result in a huge number of articles, Scopus allows only 2000 documents (currently it is 20,000) at a time to import as a .csv file which requires to repeat the procedure many times for tens or hundreds of thousands of documents. In order to reduce the workload, we opted for taking into account only the recent full year, i.e., 2022. It is important to mention that among the three types of publications mentioned above, namely journal articles, reviews, and conference papers, only those that are in English are considered in the analysis.

Several types of bibliometric analyses can be performed based on the authors, research institutions, and countries which produce the documents, but we focus here on the author-defined keywords existing in the documents. The resulting co-word analysis, also known as "author keyword co-occurrence analysis" was performed per neurotechnology dimension studied and according to the following rule: the documents found in the most prominent three subject areas, e.g., Medicine, Biochemistry, Genetics and Molecular Biology, Engineering, and Computer Science were considered and in addition, also the subject area Neuroscience is considered and the co-occurrence analysis was carried out in the VOSviewer software. This method counts the author-defined keywords used in the documents as well as the number of times these keywords are used together in two different documents. The keywords are then visualized in a network where the nodes represent the keywords and the links between a pair of nodes designate the co-occurrence relationship between two keywords. The size of the nodes measures the number of occurrences of a keyword in the documents while the width of the link measures the number of co-occurrences of a pair of nodes, i.e., the strength of the relationship.

One of the observations made during this work shows that some keywords bare the same meaning (e.g., "Data analytic" and "data analytics") and hence they should be merged. By scanning the keywords, we aimed at making the merging only in obvious cases. However, such merging should be carried out with caution: e.g., "covid-19" and "sars-cov-2" could be considered to be merged, but "covid-19" refers to the disease while "sars-cov-2" represents the virus causing the disease. Since the number of keywords is not significantly reduced by the above-mentioned merge operations, it still remains a challenge to visualize the keywords in a network in the co-word analysis. Therefore, by increasing the "minimum number of occurrences of a keyword" threshold in the VOSviewer software, we set the number of keywords represented in the co-word analysis to 100.

The results of the co-word analysis are shown in dedicated figures per neurotechnology dimension and per each subject area studied. In addition to the nodes and links representing, respectively, the number of occurrences of the keywords separately and the number of co-occurences of a pair of keywords, the VOSviewer software also clusters the keywords based on the association strength between the keywords. For this purpose, we make use of the VOSviewer's clustering algorithm (with the counting method fractional counting, and the normalization method based on association strength). The number of clusters can be chosen parametrically and, in our analysis, we set the number of clusters equal to five since it allows a meaningful representation to interpret the thematic groups within five clusters.

Note that each color in the network displayed in co-word analysis figures represents a distinct thematic cluster. The nodes and links within a cluster help explain the range of topics (nodes) covered by that theme (cluster) and how those topics (nodes) are interconnected (links) (Donthu et al., 2021). To fully interpret the results of the bibliometric analysis, our team convened to discuss the interpretation of each thematic cluster and the significance of the keywords within publications in that cluster.

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Finally, in this document, bibliometric analyses for dimensions 3 to 7 are included. The reason for that selection is that these dimensions are considered as the more suitable ones for translational innovation development, which is the focus of WP5. The presentation of the analyses will include the following structure. First the **Definition of the Dimension** will be provided, second, **Keywords Utilized** will be listed, third, the number of occurring documents and the most prominent subject areas are identified in a section called **Documents by Subject Area**, fourth, per each subject area the **Highlights** are presented to include a **Word Cloud**, and fifth the **Co-occurrence Network** will be presented both graphically and with a list of keywords occurring in each cluster. Note that, the tabulated list of keywords in the highlights sections on the right panels are ranked based on the number of occurrence and the keywords that are highlighted in yellow indicate challenges and those highlighted in green represent technologies that provide solutions. Note also that the keywords that shown in the word clouds in the left panels, which are indicated by a red rectangle show technologies and those indicated by a blue rectangle show technologies that receive relatively less attention in the state-of-the-art despite their potential to represent the more impactful topics either alone or in a complementary way as coupled to other keywords.

Bibliometric analysis results per dimension

Dimension 3: Neuromorphic Systems/Computing

Definition of the Dimension Neuromorphic systems/computing offers alternative solutions to the standard *von Neumann*-computer architecture, promising to achieve high computational densities while reducing the required power. Additionally, they can contribute to brain-compatible systems with low power consumption.

Keywords Utilized *energy efficiency, graph neural network, classification, internet of things, transfer learning, graphene, long short-term memory, covid-19, feature extraction, recurrent neural network, deep learning, convolution neural network, machine learning, neural network, artificial intelligence, CNN, artificial neural network, virtual reality, deep neural network, attention mechanism, computer vision, object detection, optimization, robustness, MRI, transformer, support vector machine, image classification, radiomics, reinforcement learning, image processing, generative adversarial network, prognosis, biomarker, signal processing, wireless sensor network, graphene oxide, training, eeg, natural language processing, task analysis, data augmentation, segmentation, edge computing, genetic algorithm, diagnosis, algorithm, clustering, semantic segmentation, breast cancer, prediction, anomaly detection, graph convolutional network, security, augmented reality, quantum dots, field programmable gate array, feature selection, deep reinforcement learning, random forest, attention, fault diagnosis, federated learning, energy consumption, bp neural network, cloud computing, image segmentation, sentiment analysis, u-net.*

Documents by Subject Area The search resulted in 470,322 documents. Figure 1. shows the distribution of documents with respect to the subject areas. The most prominent subject area is **Engineering**, which contains 99,238 documents that account for 21.1% of the overall number of documents. **Computer Science** ranks second with 98,760 documents, whereas **Physics and Astronomy** (39,291 documents) and **Neuroscience** (10,822 documents) are the third and the fourth most prominent subject areas, respectively.

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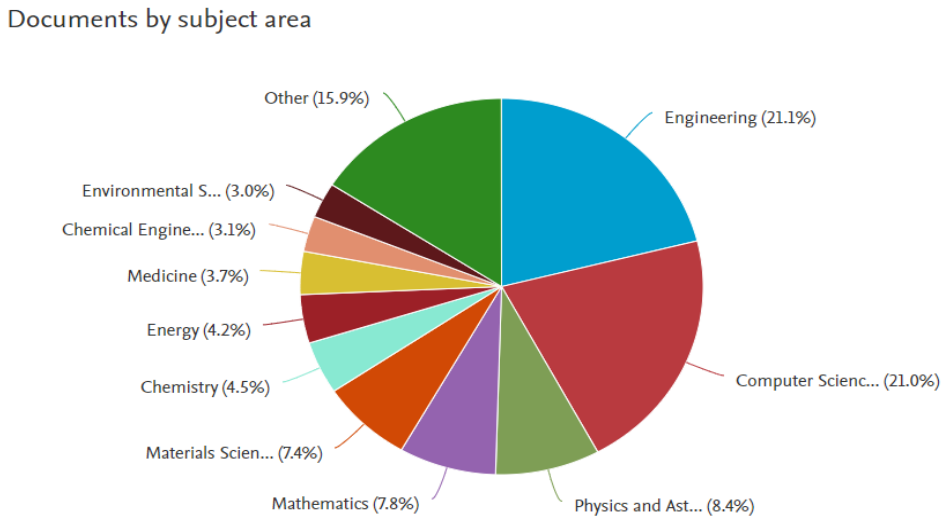


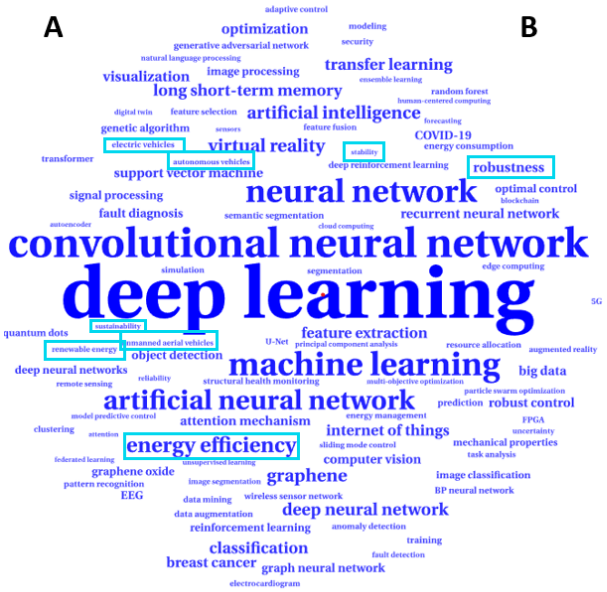
Figure 1 Pie chart illustrates the percentage of subject areas in the field of neuromorphic systems/computing.

Dimension 3 - Subject Area - Engineering

Highlights In Engineering, 99,238 documents and 179,393 author keywords were investigated. Engineering was a technology-dominant subject area and AI-based technologies dominated the area. The most occurring keyword was deep learning. Figure 2 shows the word cloud and occurrence frequency of keywords with color coding (green: technology and yellow: challenge). The key technologies were virtual reality, graphene, and IoT. The key challenges were *energy efficiency, optimization, robustness, energy consumption, renewable energy, sustainability, security, robustness, stability, unmanned aerial vehicles, and electric vehicles.*

Subject Area: Engineering (99,238 documents, 179,393 author keywords)

A



B

deep learning	9090
convolutional neural network	8210
machine learning	5112
neural network	4897
artificial neural network	3537
energy efficiency	2193
virtual reality	1592
graphene	1547
artificial intelligence	1522
deep neural network	1401
long short-term memory	1241
transfer learning	1235
classification	1226
internet of things	1092
feature extraction	1076
optimization	959
robustness	913
recurrent neural network	847
support vector machine	846
attention mechanism	798
computer vision	773
fault diagnosis	717
graph neural network	697
object detection	696

Figure 2 Word cloud (A) and the most occurring keywords of D3 - Subject area -Engineering (B).

Co-occurrence Network Figure 3 shows the co-occurrence network in five clusters.

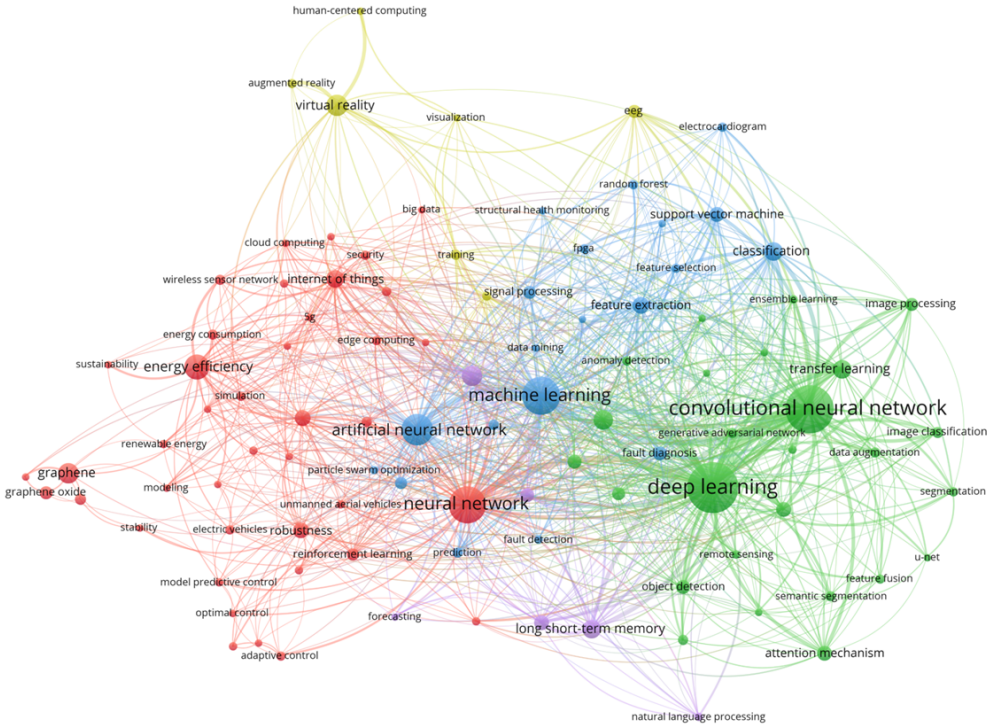


Figure 3 Keyword co-occurrence network based on author keywords of Engineering subject area.

Red cluster

AI-based technologies **neural networks, reinforcement learning.**
Other technologies **internet of things, wireless sensor networks, 5G, edge computing, cloud computing, graphene, graphene oxide, simulation, modeling, model predictive control, optimal control, adaptive control, quantum dots.**
Challenges **Energy efficiency, energy consumption, renewable energy, sustainability, security, robustness, stability, unmanned aerial vehicles, electric vehicles.**

Purple cluster

Sequential modeling techniques **long-short term memory, recurrent neural networks**
Challenges **natural language processing, forecasting.**

Yellow cluster

Technologies **virtual reality, augmented reality, visualization, human-centered computing, EEG.**

Blue cluster

AI-based technologies **machine learning, artificial neural networks, support vector machines, random forest, genetic algorithms, feature extraction/selection.**
Other technologies **ECG, field programmable gate array (FPGA), data mining.**
Challenges **classification, fault diagnosis, signal processing, structural health monitoring, and classification.**

Green cluster

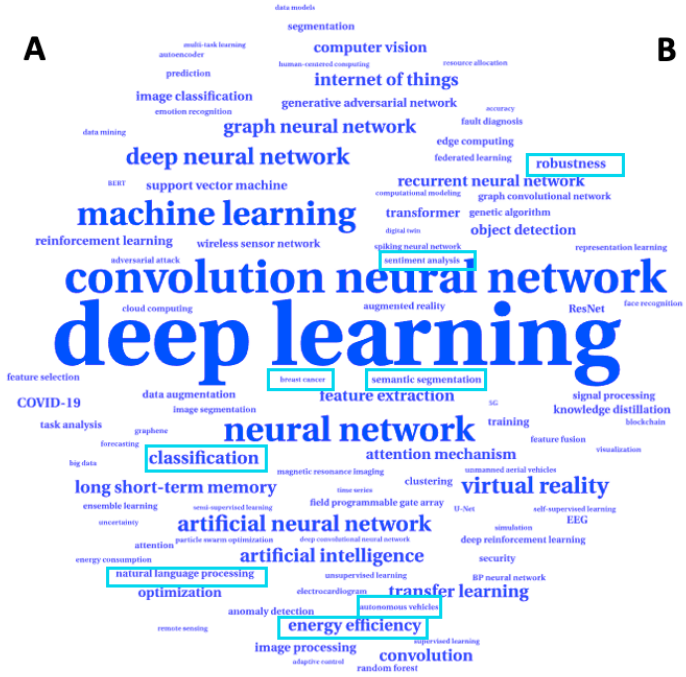
AI-based technologies **deep learning, convolutional neural network, transfer learning, ensemble learning, deep neural networks, feature fusion, graph neural networks, computer vision, u-net, generative adversarial networks**
Challenges **attention mechanism, image processing/classification, data augmentation, remote sensing, segmentation, semantic segmentation, object detection**

Dimension 3 - Subject Area - Computer Science

Highlights In Computer Science, 98,760 documents and 157,284 author keywords were investigated. Computer Science was a technology dominant subject area. AI-based technologies dominated the area. The most occurring keyword was deep learning. Figure 4 shows the occurrence frequency of keywords with color coding (green: technology and yellow: challenge). The key technologies were virtual reality, IoT, object detection. The notable technologies were task analysis, visualization, computational models, human-centered computing**.** The key challenges were *classification, energy efficiency, optimization, robustness, natural language processing, sentiment analysis, forecasting, breast cancer, semantic segmentation.*

Subject Area: Computer Science (98,760 documents, 157,284 author keywords)

A



B

deep learning	12319
convolution neural network	10967
neural network	6324
machine learning	5888
virtual reality	2771
deep neural network	2770
artificial neural network	2573
artificial intelligence	1871
graph neural network	1854
classification	1664
internet of things	1632
transfer learning	1626
long short-term memory	1545
energy efficiency	1469
feature extraction	1349
recurrent neural network	1284
attention mechanism	1160
computer vision	1138
object detection	1015
optimization	975
robustness	962

Figure 4 Word cloud (A) and the most occurring keywords of Dimension 3 - Subject area -Computer Science (B).

Co-occurrence network Figure 5 shows the co-occurrence network in five clusters.

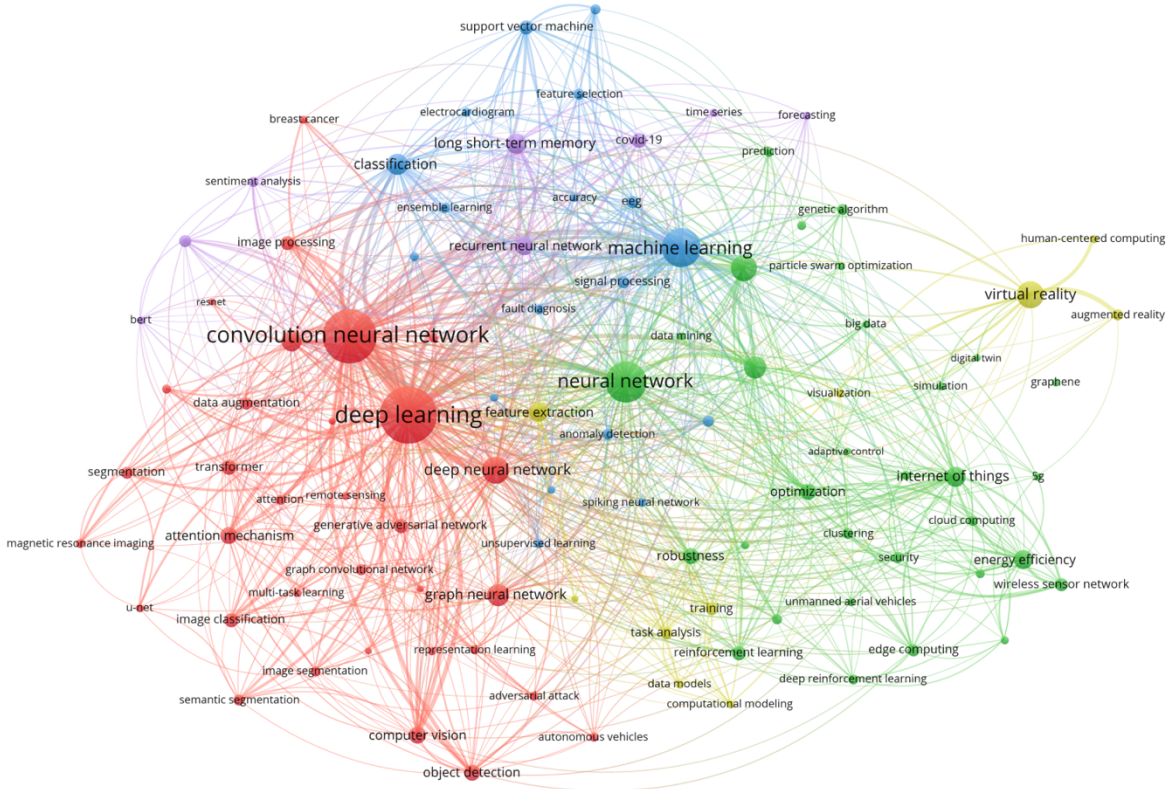


Figure 5 Keyword co-occurrence network based on author keywords of Computer Science subject area.

Red cluster

AI-based technologies **deep learning, convolutional neural networks, deep neural networks, attention mechanism, graph neural network, transfer learning, generative adversarial network, data augmentation, feature extraction, transformers, multi-task learning, graph convolutional network.**

Other technologies **MRI, computer vision, object detection, image processing, u-net.**

Challenges **breast cancer, semantic segmentation, image classification, remote sensing, attention, autonomous vehicles.**

Purple cluster

Sequential modeling techniques **long-short term memory** and **recurrent neural networks.**

Challenges **natural language processing, sentiment analysis, forecasting, covid-19, time series.**

Yellow cluster

Technologies **virtual reality, augmented reality, feature extraction, task analysis, visualization, computational models, human-centered computing.**

Blue cluster

AI-based technologies **machine learning, support vector machines, random forest, unsupervised learning, ensemble learning, feature selection.**

Medical imaging technologies **EEG and ECG.**

Challenges **fault diagnosis, anomaly detection, signal processing.**

Green cluster

AI-based technologies **neural networks, artificial neural networks, artificial intelligence, big data, reinforcement learning.**

Other technologies **internet of things, wireless sensor networks, 5G, cloud computing, optimization, genetic algorithm, particle swarm optimization.**

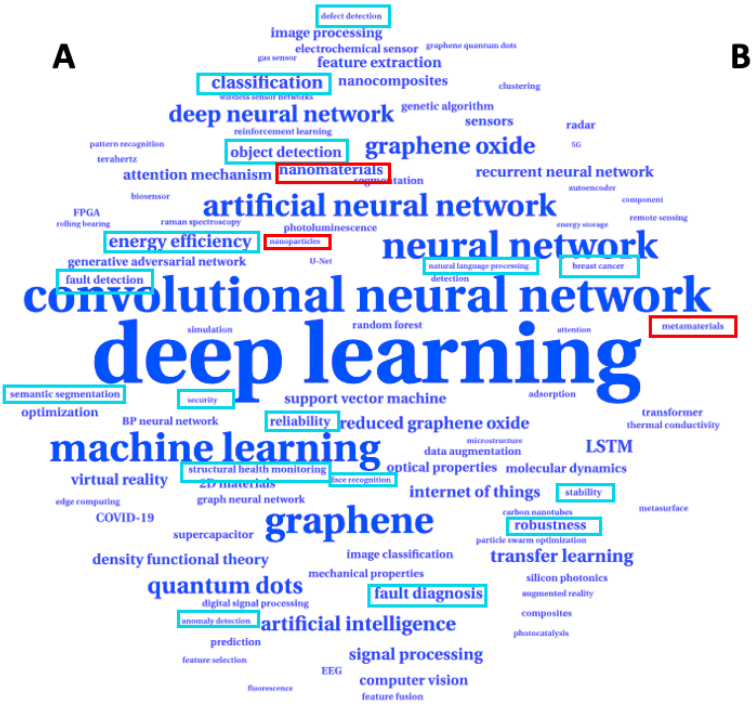
Challenges **security, robustness, unmanned aerial vehicles.**

Dimension 3 - Subject Area - Physics and Astronomy

In Physics and Astronomy subject area, 39,291 documents, 74,420 author keywords were examined. Physics and Astronomy was a technology dominant subject area. AI-based technologies dominated the area. Figure 6 shows word cloud and the occurrence frequency of keywords with color coding (green: technology and yellow: challenge). The most occurring keyword was deep learning. The notable technologies were nanomaterials, nanoparticles, metamaterials. The key challenges were *classification, energy efficiency, fault diagnosis, object detection, semantic segmentation, defect detection, structural health monitoring, energy efficiency, signal processing, face recognition, security, cancer.*

Subject Area: Physics & Astronomy (39,291 documents, 74,420 author keywords)

A



B

deep learning	2800
convolutional neural network	2559
machine learning	1677
neural network	1546
graphene	1511
artificial neural network	1011
graphene oxide	587
quantum dots	585
deep neural network	569
artificial intelligence	426
classification	345
energy efficiency	343
transfer learning	343
LSTM	331
reduced graphene oxide	301
signal processing	291
internet of things	274
fault diagnosis	263
virtual reality	242
recurrent neural network	236
density functional theory	233
feature extraction	232
attention mechanism	230
object detection	229

Figure 6 Word cloud (A) and the most occurring keywords in Dimension 3 - Subject area -Physics and Astronomy (B).

Co-occurrence network Figure 7 shows the co-occurrence network in five clusters.

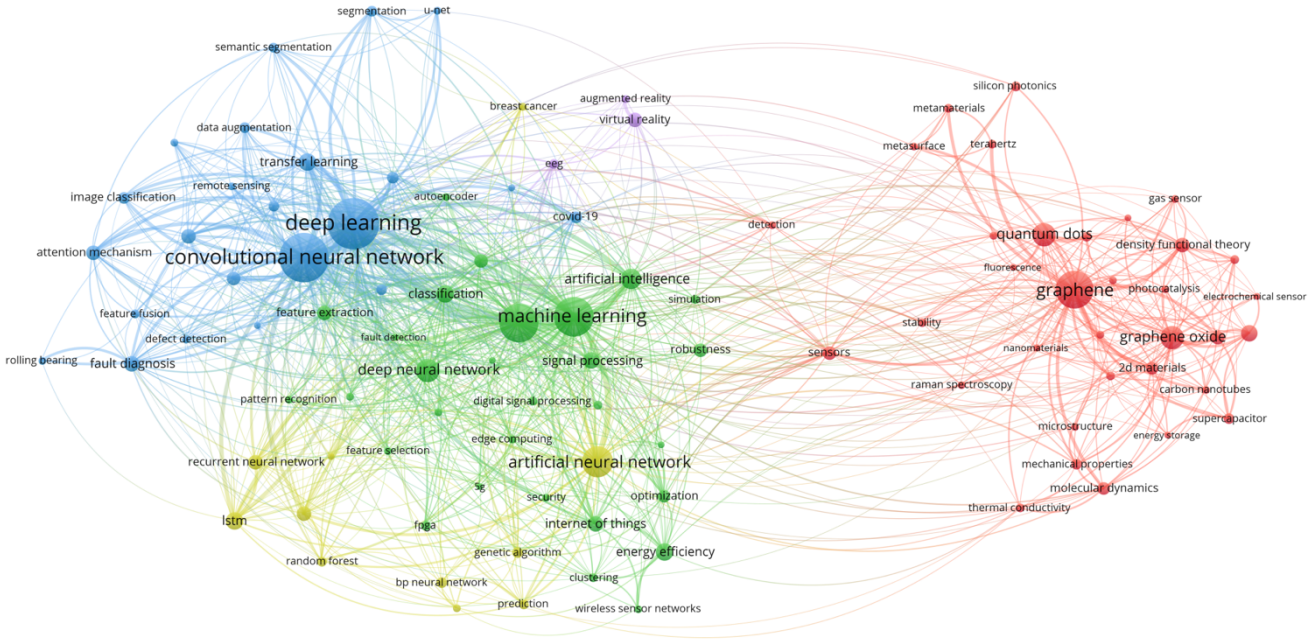


Figure 7 Keyword co-occurrence network based on author keywords of Physics and Astronomy subject area.

Red cluster

Key topics **graphene, graphene oxide, quantum dots, nanocomposites, 2D materials, silicone photonics, metamaterials, metasurface, carbon nanotubes, nanomaterials.**

Relevant technologies **molecular dynamics, mechanical properties, photoluminescence, thermal conductivity.**

Challenges **sensors, supercapacitor, biosensor, supercapacitor.**

Purple cluster

Technologies **virtual reality, EEG, augmented reality**

Yellow cluster

AI-based technologies **artificial neural networks, long short-term memory (LSTM), recurrent neural networks, support vector machine, genetic algorithms, random forest.**

Challenge **breast cancer**

Blue cluster

AI-based technologies **deep learning, convolutional neural networks (CNN), transfer learning, generative adversarial networks, graph neural network.**

Implications **fault diagnosis, attention mechanisms, data augmentation, u-net, transformer, feature fusion.**

Challenges **object detection, computer vision, image classification, semantic segmentation, defect detection, and structural health monitoring.**

Green cluster

AI-based technologies **machine learning, neural networks, deep neural networks, artificial intelligence, feature extraction, reinforcement learning.**

Other technologies **internet of things, robustness, optimization, FPGA simulation, edge computing, pattern recognitioın, wireless sensor networks.**

Challenges **energy efficiency, signal processing, face recognition, security.**

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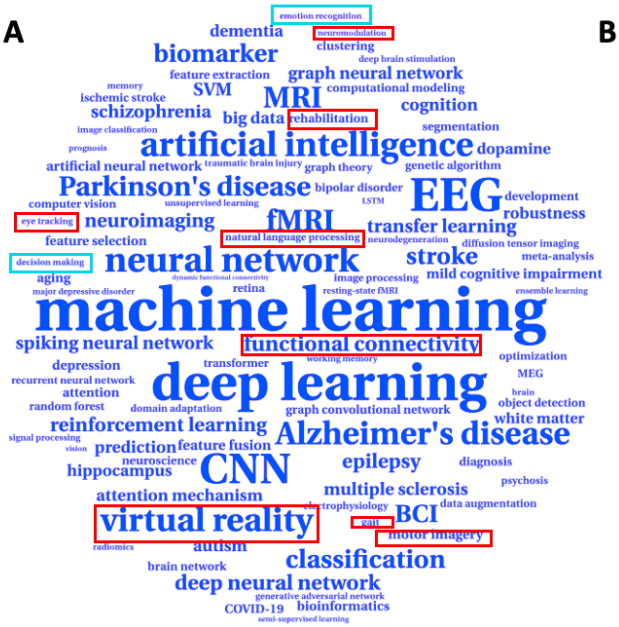
Dimension 3 - Subject Area - Neuroscience

Highlights In the Neuroscience subject area, 10,822 documents, and 20,623 author keywords were investigated. Neuroscience was a technology-dominant subject area. AI-based and medical imaging (EEG, MRI, fMRI) technologies are central. Figure 8 shows the word cloud and occurrence frequency of keywords with color coding (green: technology and yellow: challenge). The most occurring keyword was machine learning. The notable technologies were *virtual reality, gait, rehabilitation, functional connectivity, eye tracking, neuromodulation, and natural language processing*. The most common challenges were *decision-making and emotion recognition*.

Subject Area: Neuroscience (10,822 documents, 20,623 author keywords)

A



B

machine learning	815
deep learning	578
EEG	469
CNN	380
neural network	266
artificial intelligence	252
virtual reality	237
Alzheimer's disease	221
MRI	187
fMRI	182
Parkinson's disease	163
classification	144
biomarker	133
Brain computer interface	130
stroke	127
functional connectivity	113
deep neural network	109
epilepsy	99
reinforcement learning	95
neuroimaging	92
transfer learning	86

Figure 8 Word cloud (A) and the most occurring keywords in Dimension 3 - Subject area -Neuroscience (B).

Co-occurrence network Figure 9 shows the co-occurrence network in five clusters.

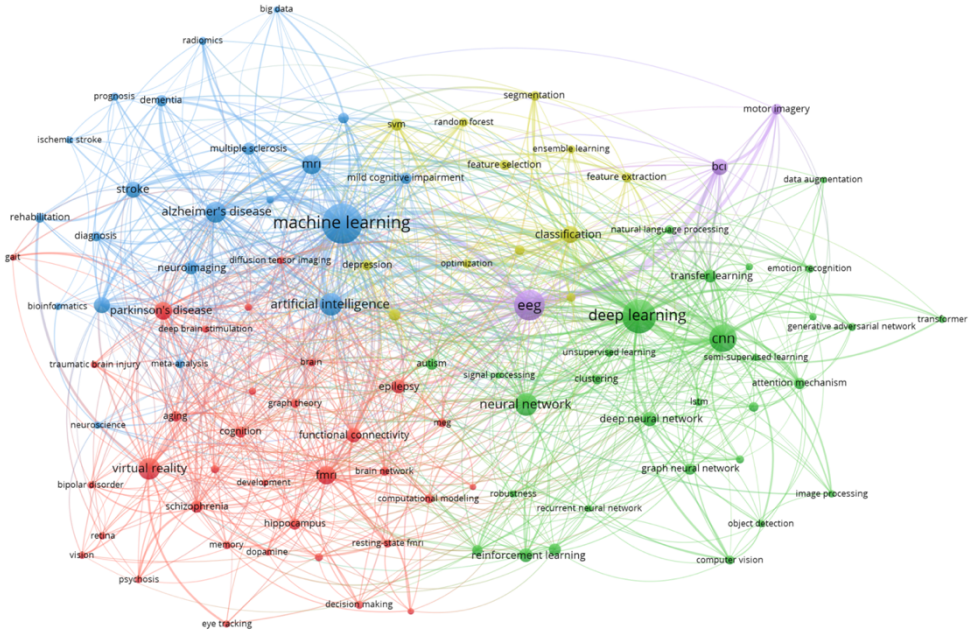


Figure 9 Keyword co-occurrence network based on author keywords of Neuroscience subject area.

Red cluster
Technologies **virtual reality, gait, functional connectivity, fMRI, MEG, diffusion tensor imaging, eye tracking, deep brain stimulation, neuromodulation.**
Challenges **Parkinson's disease, epilepsy, Schizophrenia, aging, bipolar disorder, decision making, brain network, cognition, memory, bipolar disorder.**

Purple cluster
Technologies **EEG, brain computer interface (BCI), motor imagery**

Yellow cluster
Technologies support vector machine (SVM), **genetic algorithms, random forest, classification, segmentation, feature extraction, feature selection, ensemble learning.**
Challenges **depression, Covid-19, segmentation, classification.**

Blue cluster
AI-based technologies **machine learning, artificial intelligence**
Biomedical technologies **MRI, neuroimaging, diffusion tensor imaging, biomarkers, bioinformatics, radiomics, signal processing, rehabilitation, prognosis, diagnosis, meta-analysis**
Challenges **Alzheimer's disease, stroke, ischemic stroke, dementia, multiple sclerosis, dementia, mild cognitive impairment**

Green cluster
AI-based technologies **deep learning, convolutional neural network (CNN), neural networks (NN), deep neural networks, transfer learning, spiking NN, graph NN, graph convolutional network, long short-term memory (LSTM), reinforcement learning, transfer learning, computer vision, feature extraction.**
Challenges **autism, emotion recognition, natural language processing, transformers, attention mechanism.**

Dimension 4: Neuromorphic Control/Neurorobotics

Definition of the Dimension: Neuromorphic control operates under the assumption that the biomechanics of our body perform implicit computation, which is then transmitted to the nervous system and the brain as the central controller. Applications in neurorobotics combine this neuromorphic control within the framework of interactions in the physical world, generating new theories and models of brain architecture, and solutions to complex changes in robot control.

Keywords Utilized *biomechanics, muscle mechanics, musculoskeletal, joint movement, gait analysis, electromyography, sensors, sensor systems, multisensory integration, robotics, powered prostheses, exoskeletons, power, battery, personalized diagnosis, artificial neural networks, artificial intelligence, machine learning, algorithms, controllers, bioelectronics, wearables, wireless communication, nanotechnology, neurofeedback, neurorehabilitation, neuromodulation, amputation, tactile processing, sense of touch, intelligent navigation, robotic mobility, autonomous vehicles, autonomous vehicle interaction, robot learning, stroke, cerebral palsy, spasticity, multiple sclerosis, Parkinson's disease, autism, prosthetics, virtual reality, electroencephalography (EEG), electrospinography (ESG), neurostimulation, brain-machine interface (BMI), brain-computer interface (BCI), transcranial Electrical Stimulation (tES), transcranial Direct Current Stimulation (tDCS), transcranial Alternating Current Stimulation (tACS), transcranial Random Noise Stimulation (tRNS), non-invasive brain stimulation (NIBS), transcranial magnetic stimulation (TMS).*

Documents by Subject Area The search resulted in 1,050,568 documents. Figure 10 shows the distribution of documents with respect to the subject areas. The most prominent subject

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area is **Engineering**, which contains 209,063 documents that account for 19.9% of the overall number of documents. **Computer Science** ranks second with 129,366 documents, whereas **Medicine** (122,773 documents) and **Neuroscience** (29,428 documents) are the third and the fourth most prominent subject areas, respectively.

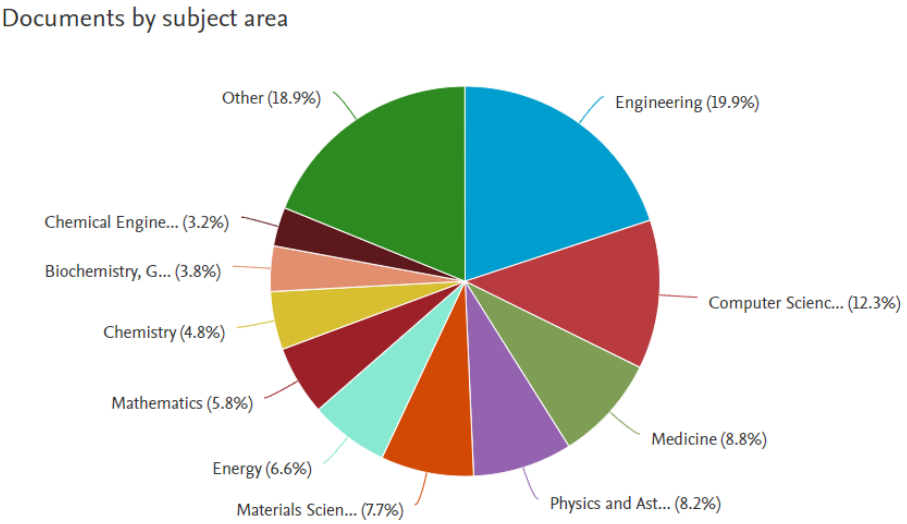

Figure 10 Pie chart illustrates the percentage of subject areas in the field of Neuromorphic Control/Neurorobotics.

Dimension 4 - Subject Area - Engineering

Highlights In the Engineering subject area, 209,063 documents, and 356,475 author keywords were investigated. Neuroscience was a technology-dominant subject area. The most occurring keyword is machine learning. The most prominent technology overall was AI-based technologies. Figure 11 shows word cloud and the occurrence frequency of keywords with color coding (green: technology and yellow: challenge). The key technologies were IoT, sensor, virtual reality, wireless sensor technologies, *lithium-ion battery, biomechanics, 3D printing*. The key challenges were *electric vehicle, autonomous vehicles, renewable energy, energy storage, energy efficiency, energy harvesting, reliability*.

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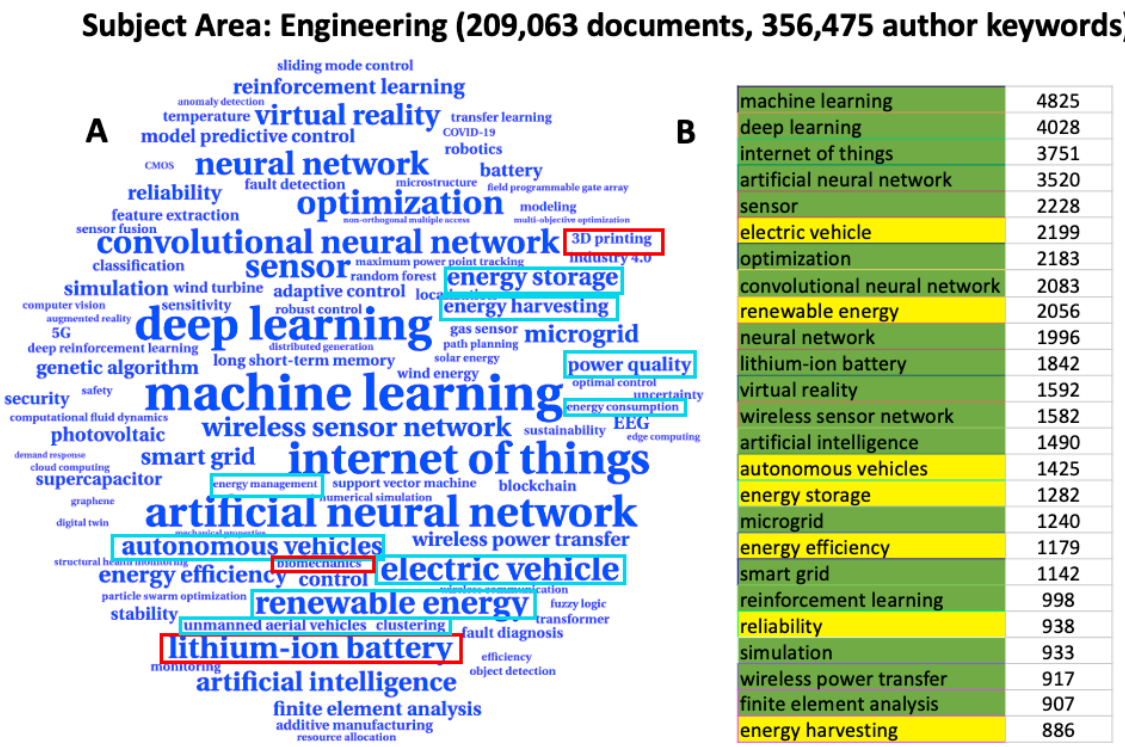

Figure 11 Word cloud (A) and the most occurring keywords in Dimension 4- Subject area – Engineering (B).

Co-occurrence network Figure 12 shows the co-occurrence network in five clusters.

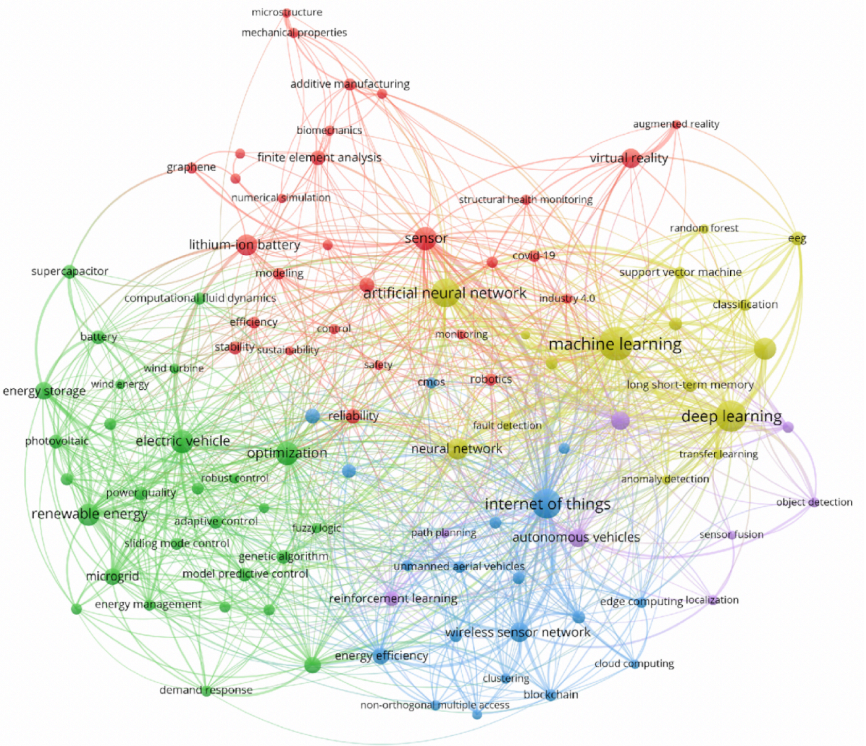

Figure 12 Keyword co-occurrence network based on author keywords of Engineering subject area.

Red cluster

Technologies **sensor, lithium-ion battery, virtual reality, simulation, FEA, robotics, additive manufacturing, modeling, graphene, biomechanics.**

Challenges **reliability, stability, efficiency, sustainability.**

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Purple cluster
Challenges **autonomous vehicles**.
Technologies **object detection**, **localization**, **sensor fusion**, **path planning, artificial intelligence, reinforcement learning.**

Yellow cluster
AI-based technologies **machine learning, deep learning, and artificial neural networks, various ML modalities random forest, convolutional neural networks, support vector machines, long short-term memory, and related technologies transfer learning, anomaly detection, feature extraction and fault detection**.
EEG as a data source.

Blue cluster
Technologies **internet of things, wireless sensor networks, edge computing, cloud computing, resource allocation, non-orthogonal multiple access and blockchain.**
Challenges **unmanned aerial vehicles, security, energy harvesting, energy efficiency, wireless power transfer and energy consumption.**

Green cluster
Technologies **(1) *optimization/control* optimization, adaptive control, robust control, various supporting techniques like sliding mode control, genetic algorithms, fuzzy logic and model predictive control. (2) *energy* renewable energy, distributed generation, microgrid, wind turbine, wind energy, photovoltaic, energy storage, supercapacitor and battery technology.**
Challenges **demand response, smart grid, energy management, electric vehicles**

Dimension 4 - Subject Area - Computer Science

Highlights In the Computer Science subject area, 129,366 documents, 226,902 author keywords were investigated. Neuroscience was a technology-dominant subject area. The most occurring keyword is IoT. The most prominent technologies overall were AI-based technologies. The key technologies were sensor, EEG, robotics, virtual reality, augmented reality. The key challenges were *autonomous vehicle, unmanned aerial vehicles, electric vehicle, energy efficiency, renewable energy, security.* Figure 13 shows word cloud and the occurrence frequency of keywords with color coding (green: technology and yellow: challenge).

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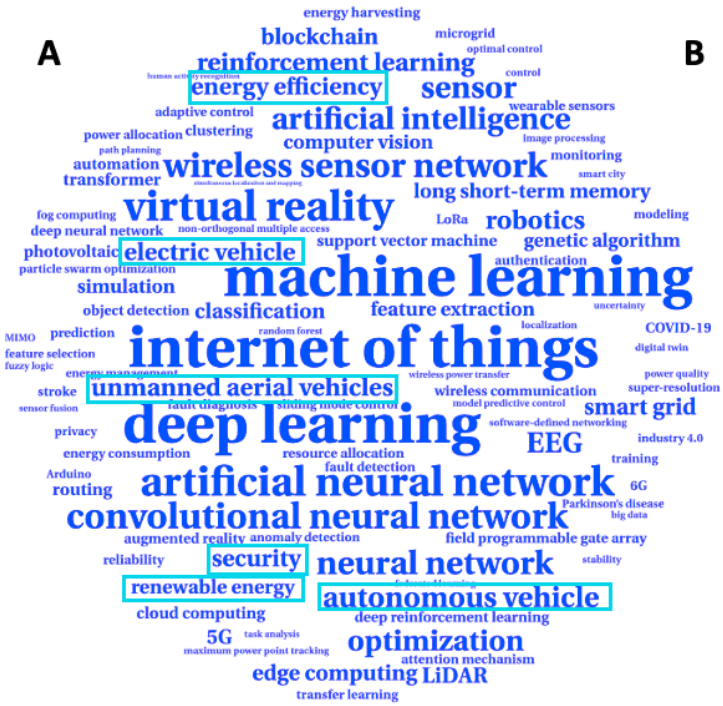
Subject Area: Computer Science (129,366 documents, 226,902 author keywords)

A



B

internet of things	4967
machine learning	4758
deep learning	4566
virtual reality	2658
artificial neural network	2561
CNN	2204
wireless sensor network	2010
neural network	1848
sensor	1647
artificial intelligence	1617
autonomous vehicle	1444
optimization	1424
EEG	1367
robotics	1140
reinforcement learning	1100
unmanned aerial vehicles	1072
electric vehicle	1020
energy efficiency	995
security	959
smart grid	903
blockchain	864
edge computing	816
classification	766
long short-term memory	702
5G	677
renewable energy	664
feature extraction	654
computer vision	651

Figure 13 Word cloud (A) and the most occurring keywords in Dimension 4 - Subject area -Computer Science (B).

Co-occurrence network Figure 14 shows the co-occurrence network in five clusters.

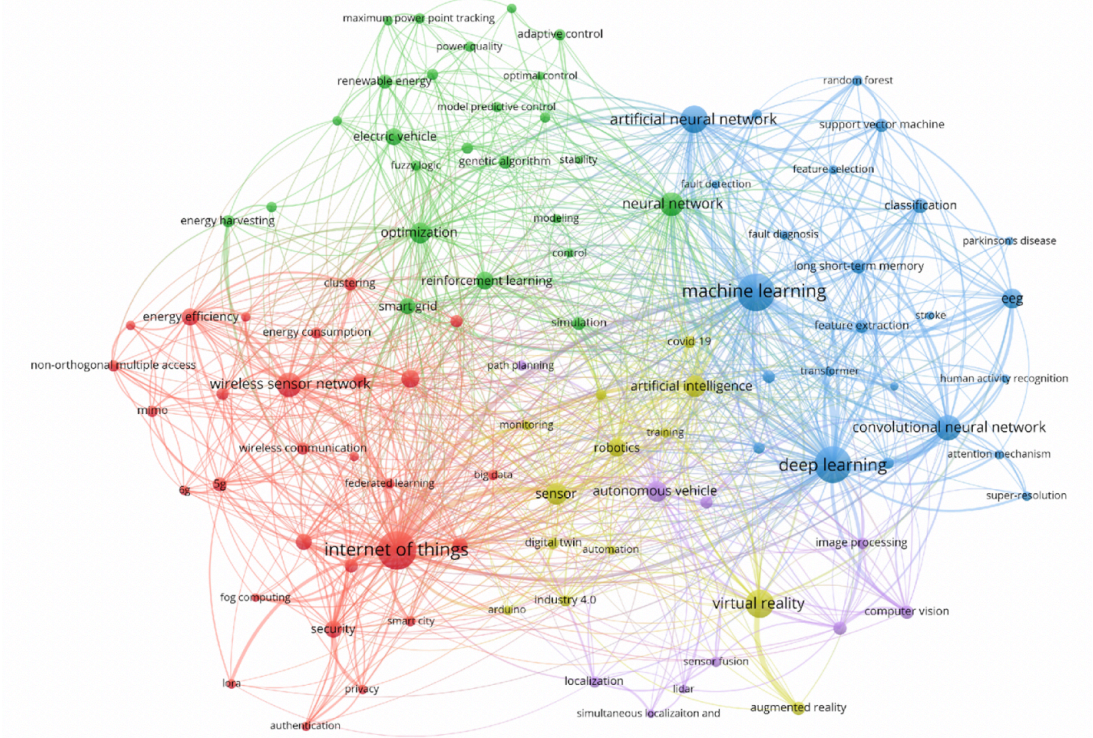


Figure 14 Keyword co-occurrence network based on author keywords of Computer Science subject area.

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Red cluster

Technologies **Internet of Things (IoT), wireless sensor networks, wireless communication, federated learning, 6G and 5G sensor clustering, non-orthogonal multiple access, multiple output and multiple input (MIMO) blockchain, decentralized computing, including edge computing, fog computing.**
Challenges **energy efficiency and energy consumption, security, privacy, authentication, unmanned aerial vehicles and smart cities.**

Yellow cluster

Technologies **virtual reality, sensor, robotics, augmented reality, digital twin, task analysis**
Challenges **industry 4.0, automation, covid-19**

Blue cluster

AI-based technologies **machine learning, deep learning, and artificial neural networks, convolutional neural networks, support vector machines, long-short term memory, random forest, feature selection/extraction,**
EEG
Implications **transformers, attention mechanisms, fault diagnosis, super resolution, fault detection, and diagnosis**
Challenges **stroke and Parkinson's disease**

Green cluster

AI-based technologies **neural network, optimization, reinforcement learning, smart grid, simulation, genetic algorithm, adaptive control, particle swarm optimization, fuzzy logic.**
Challenges **electric vehicle, energy harvesting, power quality, maximum power point tracking, wireless power transfer, energy management, stability.**

Dimension 4 – Subject Area – Medicine

Highlights In the Computer Science subject area, 122,773 documents and 174,749 author keywords were investigated. Medicine was a challenge-dominant subject area. Yet, the most occurring keyword is machine learning. The key or notable technologies were MRI, *biomarker, rehabilitation,* meta-analysis, *EEG, biomechanics, electromyography, gait, robotic surgery, neuromodulation*. The most prominent challenge overall was stroke. The most prominent technologies AI-based technologies. The key challenges were stroke related conditions, Parkinson's disease, MS, mortality, and depression. Figure 15 shows word cloud and the occurrence frequency of keywords with color coding (green: technology and yellow: challenge).

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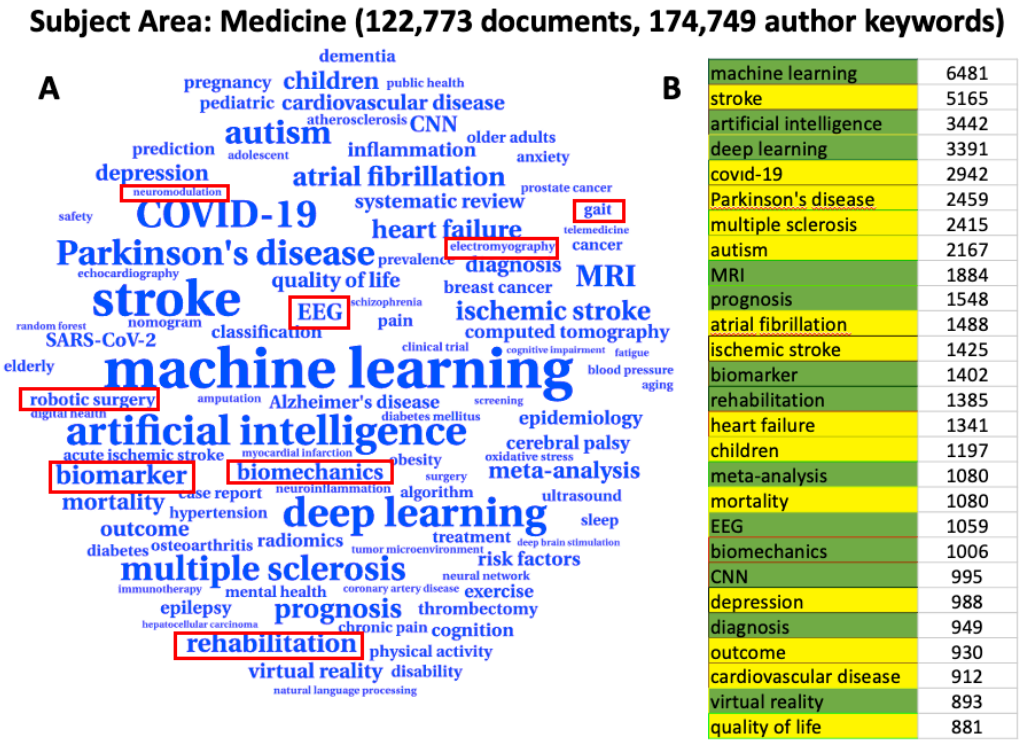

Figure 15 Word cloud (A) and the most occurring keywords in Dimension 4 - Subject area -Medicine (B).

Co-occurrence network Figure 16 shows the co-occurrence network in five clusters.

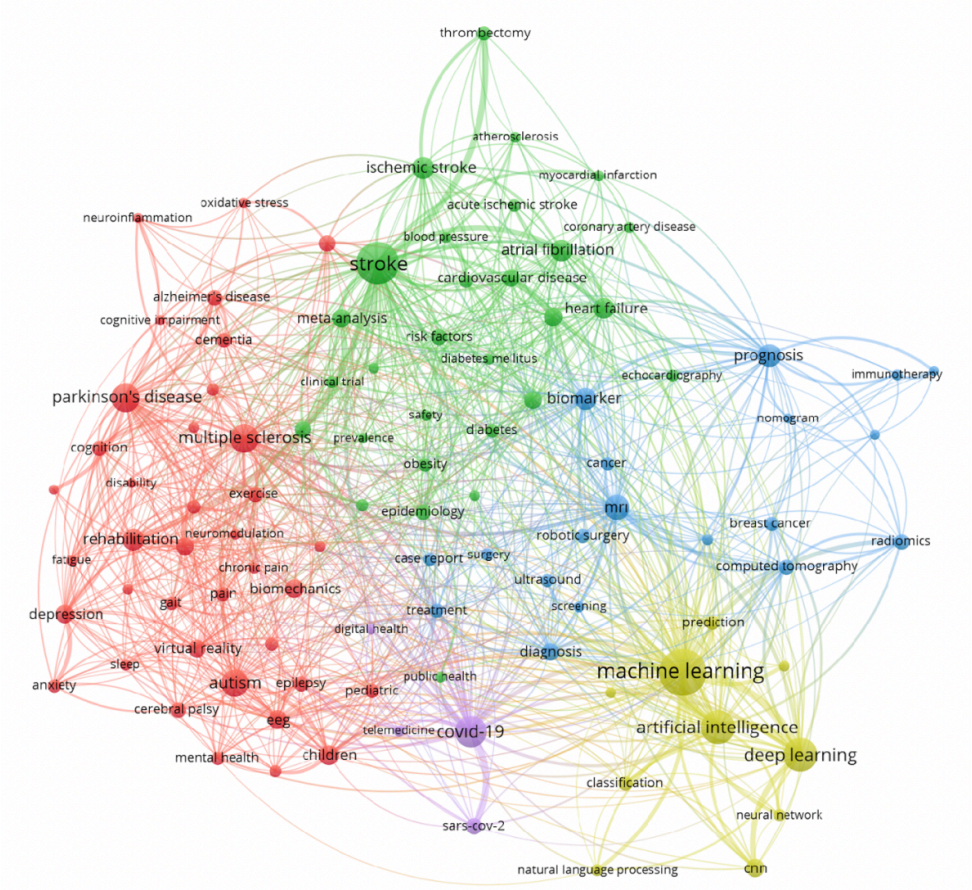

Figure 16 Keyword co-occurrence network based on author keywords of Medicine subject area..

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Red cluster
Challenges **Parkinson's disease, multiple sclerosis, autism, and cerebral palsy.**
Implications **disability, pain, fatigue.**
Technologies **rehabilitation, biomechanics, gait analysis, virtual reality, EEG and neuromodulation.**

Yellow cluster
Technologies **machine learning, artificial intelligence, deep learning, neural network, convolutional neural network (*AI-based technologies*).**
Challenges **prediction, classification, natural language processing.**

Blue cluster
Technologies (medical imaging) **MRI, computed tomography, ultrasound, and radiomics.**
Technologies ***(medical instrumentation)*** **biomarker, robotic surgery.**
Challenges **prognosis, screening, diagnosis, treatment, cancer, breast cancer.**

Green cluster
Challenges shaped around **stroke featuring.**
- closely related conditions: **ischemic stroke.**
- conditions causing stroke: **atrial fibrillation, heart failure, cardiovascular disease, coronary artery disease, myocardial infarction, obesity, diabetes.**

Dimension 4 – Subject Area – Neuroscience

Highlights In the Neuroscience subject area, 29,428 documents, 49,261 author keywords were investigated. Neuroscience was a challenge-dominant subject area. The highest occurring keyword and most prominent challenge Parkinson's disease. The key challenges were stroke, MS, autism, Alzheimer's disease The most prominent challenge overall was stroke. The notable challenge was cognition. The key or *notable technologies* were
biomarker
- Medical imaging based: EEG, MRI, fMRI,
- AI-based: deep learning, machine learning,
- *Rehabilitation-based: neuromodulation, motor control, gait, EMG.*

Figure 17 shows word cloud and the occurrence frequency of keywords with color coding (green: technology and yellow: challenge).

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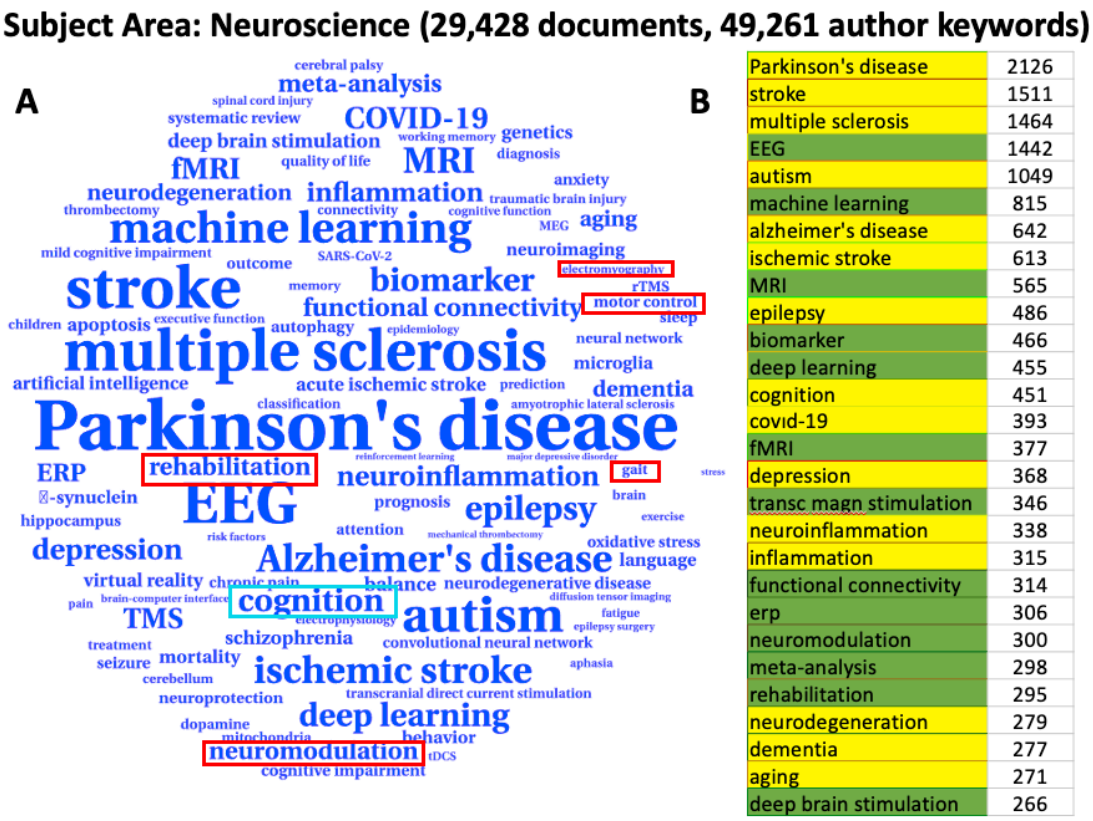

Figure 17 Word cloud (A) and the most occurring keywords of Dimension 4 - Subject area -Neuroscience (B)

Co-occurrence network Figure 18 shows the co-occurrence network in five clusters.

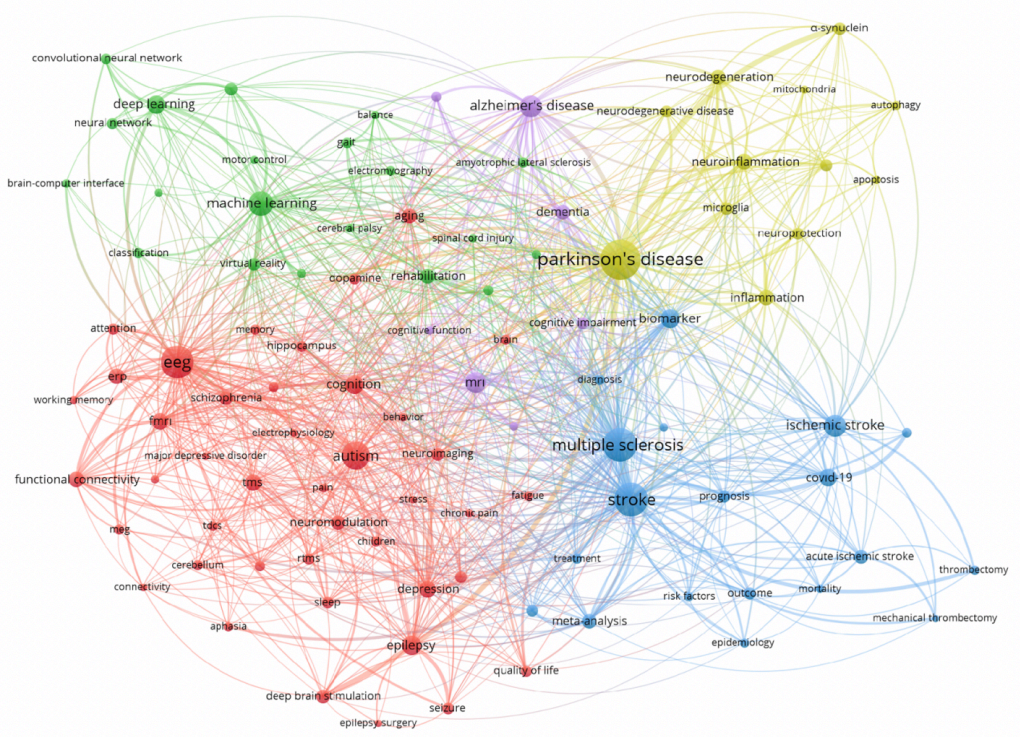

Figure 18 Keyword co-occurrence network based on author keywords of Neuroscience subject area.

Red cluster
Challenge pole **autism, cognition, epilepsy, schizophrenia, major depressive disorder, depression, attention.** Furthermore, **sleep, pain, stress, aphasia, quality of life.**
Technology pole imaging modalities and implications **EEG, fMRI, neuroimaging, magnetoencephalography functional connectivity.**
neural and brain stimulation technologies **neuromodulation, deep brain stimulation, transcranial magnetic stimulation,** and **transcranial direct current stimulation.**

Purple cluster
Challenges **Alzheimer's disease, dementia, cognitive impairment.**
Technologies **MRI, DTI.**

Yellow cluster
Challenges **shaped around Parkinson's Disease featuring neurodegeneration, inflammation, neuroinflammation, and keywords in the mechanism microglia, mitochondria, α-synuclein.**

Blue cluster
Challenges **stroke** in combination with **(acute) ischemic stroke receives major attention, multiple sclerosis** is also central.
Technologies, prediction/solution techniques **outcomes, risk factors, mortality, diagnosis, prognosis, thrombectomy, meta analysis, biomarkers.**

Green cluster
AI-based technologies, including **machine learning, deep learning,** and **neural networks, CNN.** *Data fed* **EEG, MRI, and biomarkers** from other clusters and **EMG** from this cluster
Rehabilitation technologies **gait analyses** combined with **EMG, virtual reality balance, motor control,** and **gait.**
Challenges **traumatic brain injury, amyotrophic lateral sclerosis, spinal cord injury,** and **cerebral palsy.**

Dimension 5: Neuroinformatics

Definition of the Dimension The tools for studying and analyzing the brain will converge with those used in neurotechnology applications. It is therefore strategic to develop converging methods and tools to enhance coherence and synergy between neuroscience and neurotechnology, the main challenge being the formulation of a multiscale theory of the brain, a core activity within neuroinformatics.

Keywords utilized *meta-analysis, MRI, deep learning, machine learning, systematic review, ANN, covid-19, CNN, modelling, image processing, prognosis, neural network, biomarker, stroke, case report, heart failure, visualization, artificial intelligence, children, IoT, fMRI, optimization, depression, survival, pet, image segmentation, feature extraction, imaging, genetic algorithm, computational modeling, breast cancer, segmentation, simulation, classification, diagnosis, CFD, sars-cov-2, task analysis, mortality, Alzheimer's disease, prostate cancer, risk factor, hepatocellular carcinoma, cancer, neuroimaging, computer vision, transformer, multiple sclerosis, pediatric, numerical modelling, finite element analysis, radiomics, immunotherapy, training, mathematical modeling, surgery, gan, additive manufacturing, epidemiology, obesity, blockchain, outcome, inflammation, transfer learning, exercise, ischemic stroke, treatment, deep neural network, ultrasound, functional connectivity, attention mechanism, pregnancy, svm, cognition, network meta-analysis, numerical simulation, LSTM, virtual reality, radiotherapy quality of life, prevalence, mental health, object detection, natural language processing, epilepsy, prediction model, anxiety*

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Documents by subject area The search resulted in 788,205 documents the distribution of which with respect to the subject areas is shown in Figure 19. The most prominent subject area is **Engineering** which contains 119,019 documents that account for 15.1% of the overall number of documents. **Medicine** ranks second with 117,320 documents, whereas **Computer Science** (99,476 documents) and **Neuroscience** (21,468 documents) are the third and the fourth most prominent subject areas, respectively.

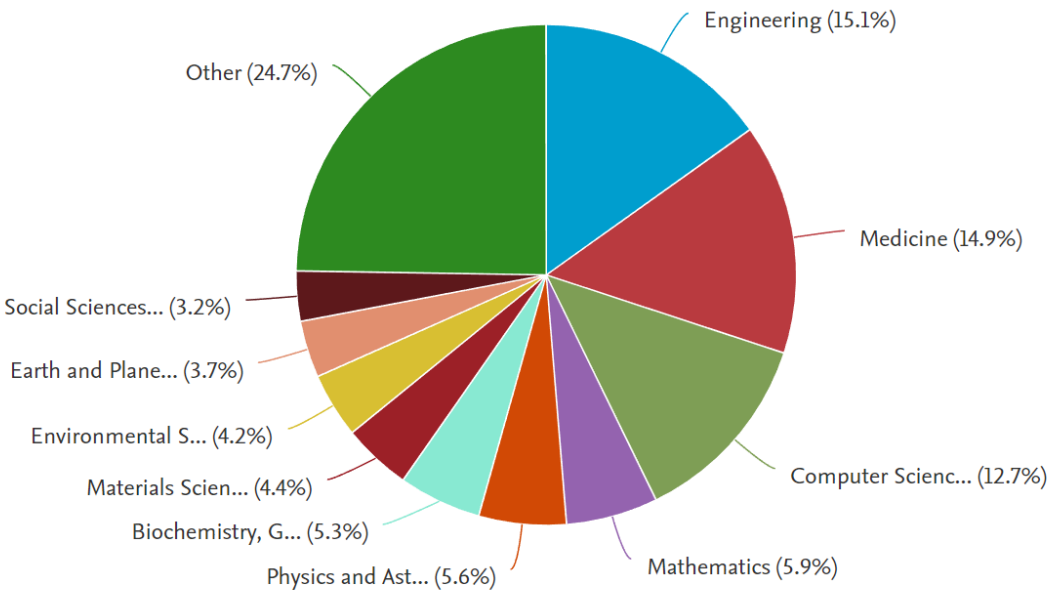

Figure 19 The pie chart illustrates the percentage of subject areas in the field of Neuroinformatics.

Dimension 5 - Subject Area - Engineering

Highlights In Engineering, 119,019 documents and 238,944 author keywords were investigated. Engineering was a technology-dominant subject area. The most occurring keyword was deep learning, Figure 20 shows word cloud and the most occurring keywords. The key technologies were AI-based: deep learning, machine learning, feature extraction, IoT, modeling based (mathematical/numerical/computational modeling, FEM/FEA, CFD, optimization, simulation, (medical) imaging based: image processing, visualization, MRI, segmentation, 3D printing, additive manufacturing. The most prominent technologies overall were AI-based.

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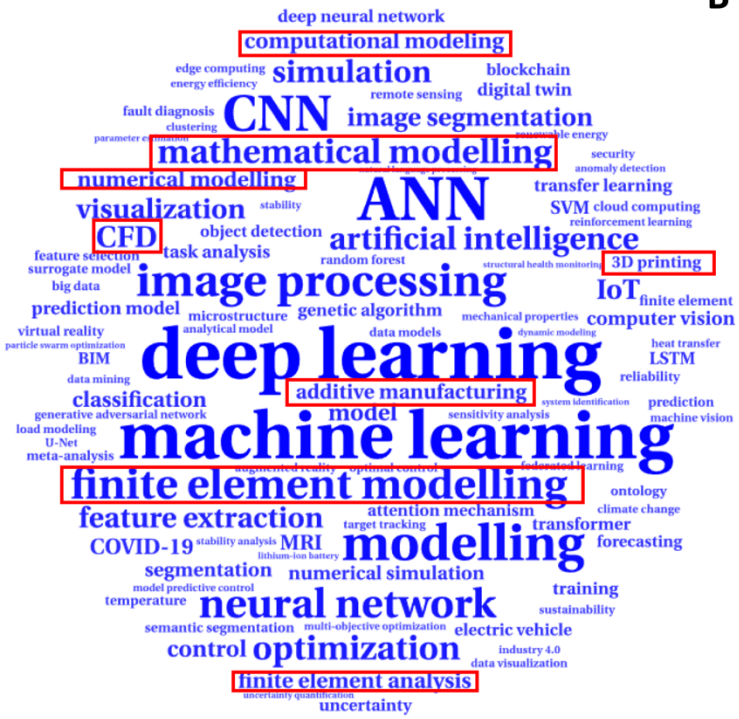
Subject Area: Engineering (119,019 documents, 238,944 author keywords)

A



B

deep learning	4834
machine learning	4235
ANN	3594
modelling	2423
CNN	2399
image processing	1954
finite element modelling	1828
neural network	1681
mathematical modelling	1270
optimization	1264
artificial intelligence	1111
simulation	1058
CFD	969
feature extraction	929
visualization	855
IoT	844
image segmentation	830
computational modeling	787
numerical modelling	780
finite element analysis	778
covid-19	761
classification	754
MRI	722
additive manufacturing	708
segmentation	641
computer vision	616
numerical simulation	609

Figure 20 Word cloud (A) and the most occurring keywords of Dimension 5 - Subject area -Engineering (B).

Co-occurrence network Figure 21 shows the co-occurrence network in five clusters.

Figure 21. Keyword co-occurrence network based on author keywords of Engineering subject area.

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Red cluster
Main Technology **Artificial Neural Networks**
Group 1 (modeling and control) **modeling (finite element, mathematical, numerical), optimization, simulation, computational fluid dynamics (CFD), genetic algorithms, uncertainty, numerical simulation, reliability, multi-objective optimization, surrogate models, stability, optimal control, dynamic modeling**
Group 2 (3D Printing) **additive manufacturing, 3D printing, mechanical properties, temperature, heat transfer**
Challenges **electric vehicle, renewable energy, energy efficiency, climate change, structural health monitoring**

Purple cluster
Technologies (model and diagram generation) **visualization, computational modeling, task analysis, feature extraction, training, prediction models**

Yellow cluster
AI-based technologies **neural networks, machine learning, support vector machines, long short-term memory (LSTM), random forest**
Challenges **forecasting, prediction, classification**

Green cluster
Main Technologies **Artificial intelligence and IoT**
Technologies **digital twin, bioinformatics and modeling (BIM), blockchain, virtual reality, big data, data mining, industry 4.0**
Challenges **covid-19, sustainability, security**

Blue cluster
Technologies (AI-based and medical imaging) **deep learning, convolutional neural networks (CNN), deep neural networks, transfer learning, transformers, MRI, u-net, image processing segmentation, computer vision**
Challenges **object detection, remote sensing**

Dimension 5 - Subject Area - Medicine

Highlights In Medicine, 117,320 documents, and 158,801 author keywords were investigated. In medicine, both challenges and technologies characterize the subject area. The most occurring keyword is meta-analysis. Figure 22 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge). The key technologies were medical data-based: meta-analysis, systematic review, prognosis, biomarker, diagnosis, medical imaging-based: MRI, computed tomography, neuroimaging, radiomics, fMRI, and AI-based: deep learning, machine learning, artificial intelligence**.** The most prominent challenges were *stroke, depression, cancer, Alzheimer's disease, and MS.*

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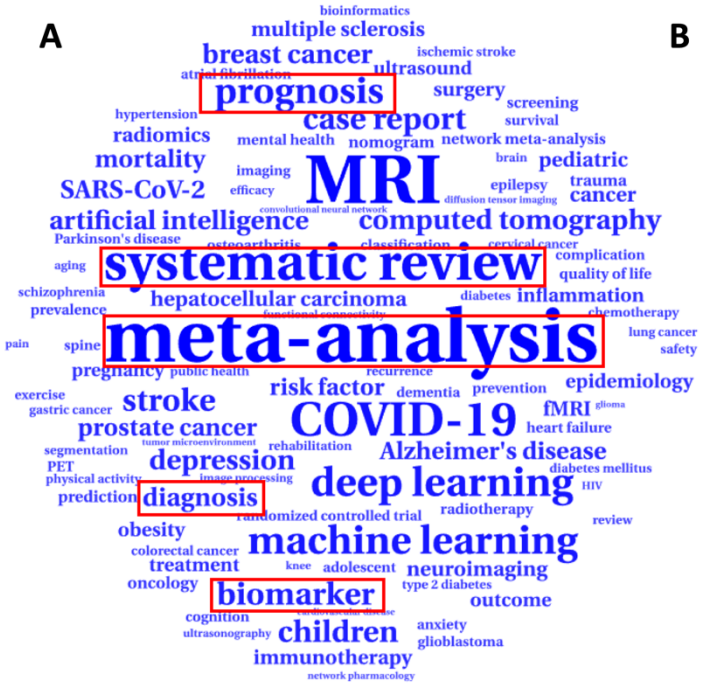
Subject Area: Medicine (117,320 documents , 158,801 author keywords)

A



B

meta-analysis	7942
MRI	6647
systematic review	3902
covid-19	3217
deep learning	2334
machine learning	2233
prognosis	1890
biomarker	1409
stroke	1409
case report	1395
children	1314
depression	1140
computed tomography	1138
breast cancer	1071
artificial intelligence	1039
diagnosis	974
sars-cov-2	965
mortality	901
alzheimer's disease	890
prostate cancer	888
risk factor	836
hepatocellular carcinoma	804
cancer	800
neuroimaging	799
multiple sclerosis	790
pediatric	790
radiomics	762
fMRI	755

Figure 22 Word cloud (A) and the most occurring keywords of Dimension 5 - Subject area – Medicine (B).

Co-occurrence network Figure 23 shows the co-occurrence network in five clusters**.**

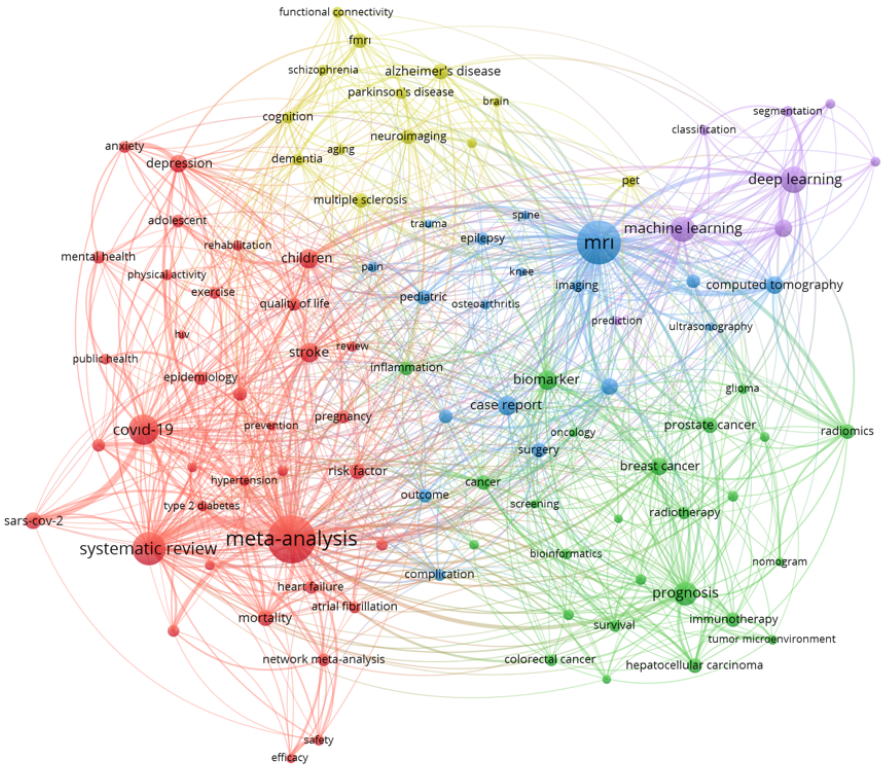


Figure 23. Keyword co-occurrence network based on author keywords of Medicine subject area.

Red cluster
Systematic analysis techniques **meta-analysis, systematic review, risk factor, epidemiology, network meta-analysis, randomized control trial, review**
Challenges **COVID-19, stroke, depression, obesity, pregnancy, quality of life, mental health, anxiety, mortality, atrial fibrillation, ischemic stroke, hypertension, diabetes, cardiovascular disease, HIV**

Purple cluster
AI-based Technologies **deep learning, machine learning, artificial intelligence, convolutional neural networks, segmentation**
Challenges **classification, prediction**

Yellow cluster
Technologies **neuroimaging, fMRI, PET, functional connectivity, diffusion tensor imaging**
Challenges **Alzheimer's disease, multiple sclerosis, cognition, dementia, Parkinson's disease schizophrenia, aging**

Green cluster
Challenges **cancer (breast, prostate, colorectal, lung cervical, gastric, hepatocellular carcinoma, glioma, glioblastoma), inflammation**
Technologies **prognosis, biomarker, radiomics, immunotherapy, radiotherapy, chemotherapy, network pharmacology, nomogram**

Blue cluster
Technologies (medical imaging) **MRI, computed tomography, ultrasound**
Challenges **case report, diagnosis, pediatric, surgery, outcome, complication, epilepsy, pain, osteoarthritis, trauma, knee, spine**

Dimension 5 - Subject Area – Computer Science

Highlights In Computer Science, 99,476 documents and 186,813 author keywords were investigated. Computer science is a technology-dominant subject area. The most occurring keyword is deep learning. Figure 24 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge). The key technologies were AI-based (deep learning, machine learning, feature extraction), IoT, modeling, computational modeling, optimization and medical imaging based (image processing, image segmentation, MRI). The most prominent technologies overall were AI-based.

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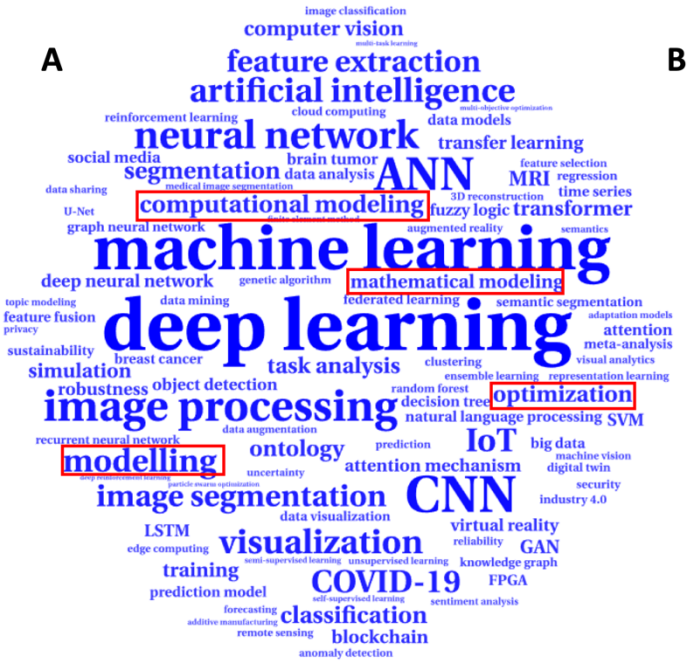
Subject Area: Computer Science (99,476 documents , 186,813 author keywords)

A



B

deep learning	6377
machine learning	4689
CNN	3177
ANN	2624
image processing	2278
neural network	1881
visualization	1371
artificial intelligence	1355
IoT	1282
modelling	1241
covid-19	1197
image segmentation	1117
feature extraction	1108
computational modeling	1077
segmentation	1071
classification	1035
optimization	947
ontology	941
task analysis	915
MRI	796
computer vision	791
transformer	791

Figure 24 Word cloud (A) and the most occurring keywords of Dimension 5 - Subject area – Computer Science (B).

Co-occurrence network Figure 25 shows the co-occurrence network in five clusters**.**

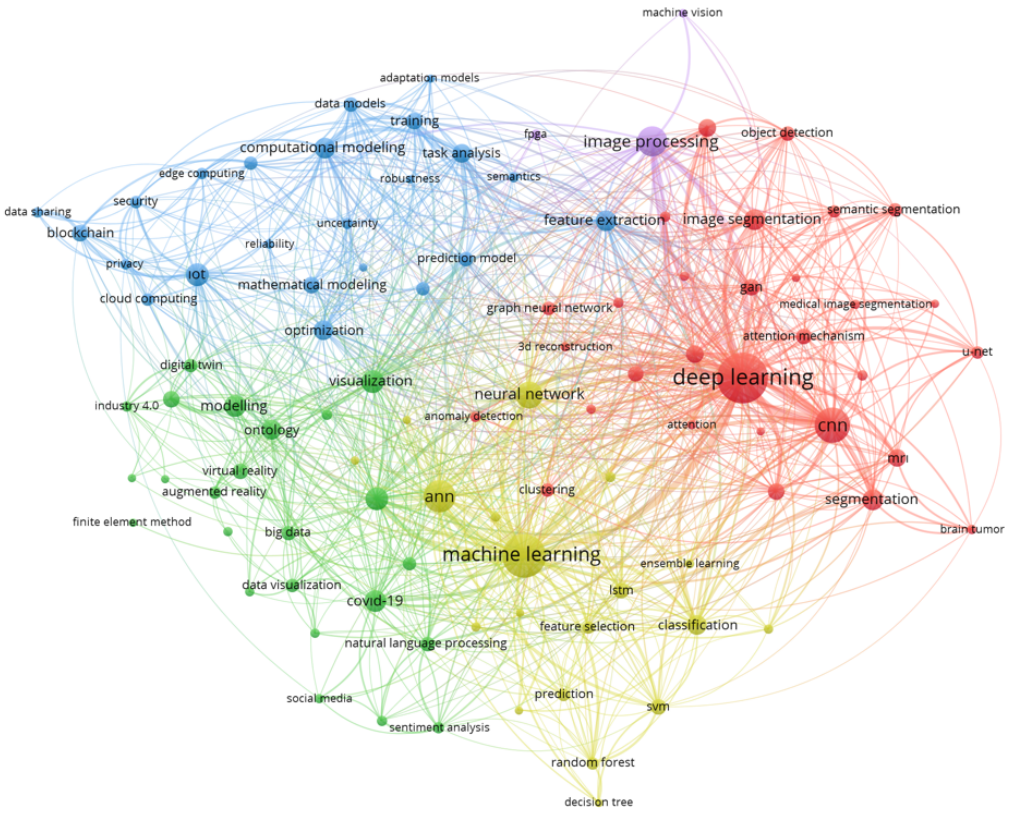


Figure 25. Keyword co-occurrence network based on author keywords of Computer Science subject area.

Red cluster
AI-based technologies **deep learning, convolutional neural networks, generative adversarial networks (gan), deep neural network**
Imaging-based technologies **MRI, u-net transformer, transfer learning, representation learning, image segmentation, clustering**
Challenges **semantic segmentation, image classification, computer vision, object detection, brain tumor**

Purple cluster
Technologies **image processing, FPGA,** and **machine vision**

Yellow cluster
AI-based technologies **machine learning**, **artificial neural networks, neural networks, support vector machines, long short-term memory, random forest, decision tree**
Challenges **classification, prediction, feature selection, ensemble learning, breast cancer** and **forecasting**

Green cluster
Technologies (modeling and visualization) **visualization, modeling, ontology, simulation, virtual reality, digital twin, augmented reality, topic modeling knowledge graph, data visualization**
AI-related technologies **artificial intelligence, natural language processing, big data, data mining, sentiment analysis**
Challenges **industry 4.0, social media**

Blue cluster
Technologies (wireless connectivity) **IoT, blockchain, cloud computing, security, edge computing, privacy**
Technologies (modelling) **computational modeling, optimization, task analysis, mathematical modeling, data models, robustness**

Dimension 5 - Subject Area – Neuroscience

Highlights In Neuroscience, 21,468 documents and 37,341 author keywords were investigated. Both challenges and technologies characterize the subject area. Figure 26 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge, blue: other relevant keywords). The key technologies were medical imaging based: MRI, fMRI, functional connectivity, neuroimaging, DTI, EEG, PET and the notable technologies were medical data based: meta-analysis, biomarker, systematic review and AI-based: machine learning, deep learning. The most prominent challenges *were Alzheimer's disease, stroke and MS*.

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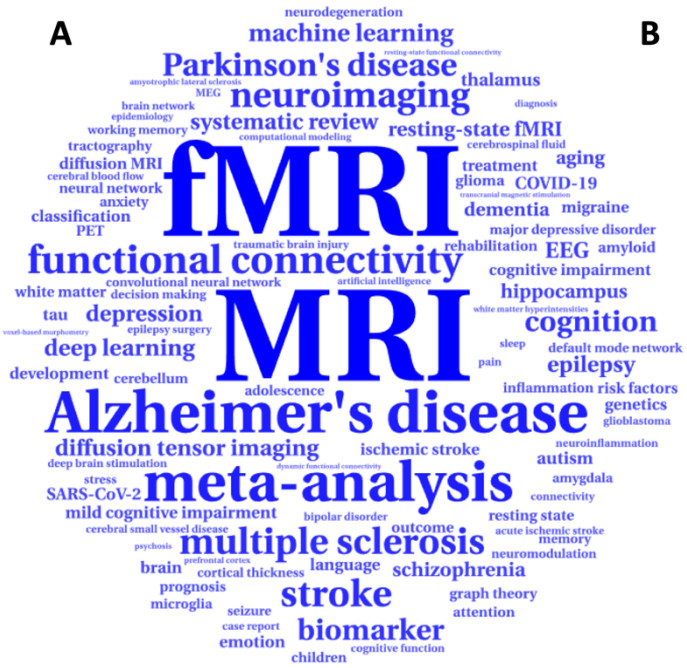
Subject Area: Neuroscience (21,468 documents , 37,341 author keywords)

A



B

MRI	1304
fMRI	1272
Alzheimer's disease	856
meta-analysis	777
functional connectivity	636
stroke	574
multiple sclerosis	549
neuroimaging	519
parkinson's disease	481
cognition	404
biomarker	401
machine learning	400
deep learning	358
diffusion tensor imaging	344
depression	340
systematic review	336
epilepsy	335
EEG	323
resting-state fMRI	320
schizophrenia	301
hippocampus	290
dementia	274
aging	273
covid-19	227
autism	225
mild cognitive impairment	213
brain	201
ischemic stroke	199
cognitive impairment	190
white matter	172
PET	170

Figure 26 Word cloud (A) and the most occurring keywords of Dimension 5 - Subject area – Neuroscience (B).

Co-occurrence network Figure 27 shows the co-occurrence network in five clusters**.**

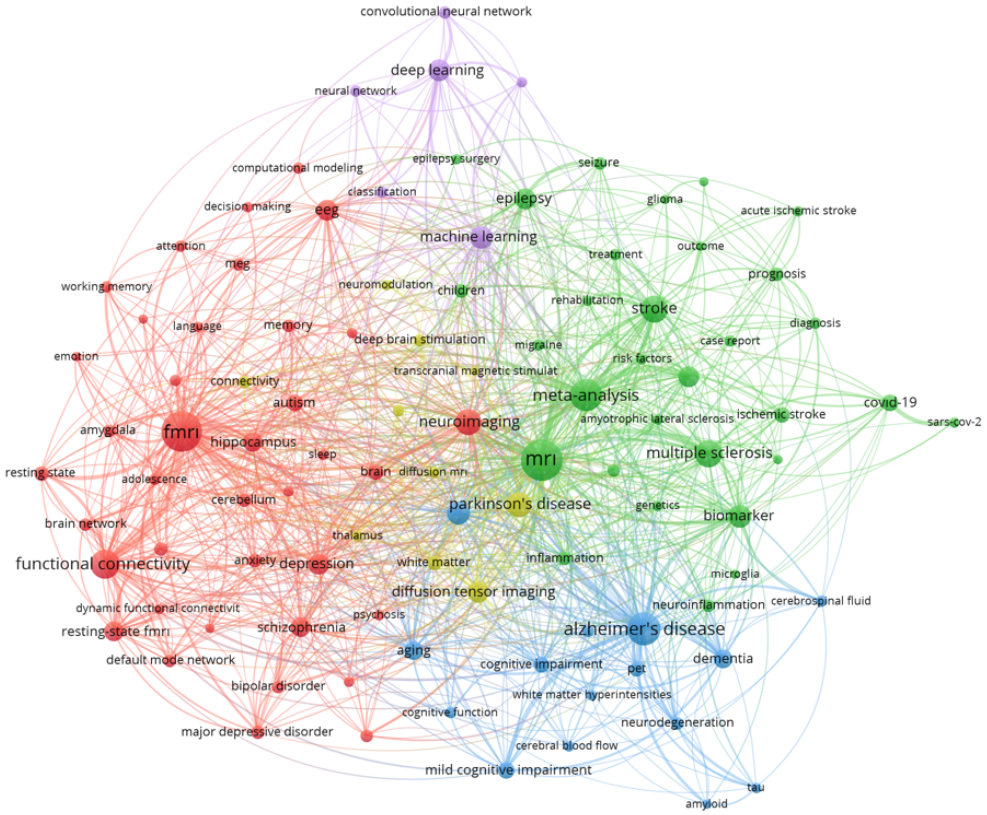


Figure 27. Keyword co-occurrence network based on author keywords of Neuroscience subject area.

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Red cluster
Technologies (medical imaging centered) **fMRI, neuroimaging, EEG, resting-state fMRI, magnetoencephalography (MEG), functional connectivity, graph theory, brain network, computational modeling**
Significant topics **hippocampus, brain, cerebellum, amygdala, memory, cortical thickness**
Challenges **depression, schizophrenia, autism, anxiety, major depressive disorder, stress, bipolar disorder, psychosis, sleep, anxiety, decision-making**

Purple cluster
AI-based technologies **machine learning, deep learning, convolutional neural networks, artificial intelligence**
Challenges **classification**

Yellow cluster
Main Challenge **Parkinson's disease**
Related topics **connectivity, white matter, thalamus**
Technologies (medical imaging centered) **diffusion tensor, imaging, diffusion MRI, tractography**
Technologies **Deep brain stimulation, neuromodulation, transcranial magnetic stimulation**

Green cluster
Technologies **MRI, meta-analysis, biomarkers, systematic review, case report, rehabilitation, epilepsy surgery**
Challenges **stroke, multiple sclerosis, epilepsy, covid-19, ischemic stroke, inflammation, prognosis, diagnosis, seizure, neuroinflammation, traumatic brain injury**

Blue cluster
Challenges **Alzheimer's disease, cognition, dementia, mild cognitive impairment, aging, neurodegeneration, cognitive impairment**
Significant topics **PET, Amyloid, Tau, cerebral blood flow, white matter hyperintensities**
Technologies **PET**

Dimension 6: Neuroprosthetics

Definition of the Dimension Neuroprosthetics represents a paradigmatic dimension in neurotechnology as they combine the perception of brain activity with its functional transformation and ultimately result in functional modulation of this brain activity. Each of the stages of a feedback system (neuroprosthetics are built on) presents numerous scientific and technological challenges. The dimension of neuroprosthetics builds upon the progress made in other dimensions.

Keywords utilized *cognitive augmentation, bioelectronics, brain-computer interfaces, electroencephalogram (EEG), transcranial magnetic stimulation, neuromodulation, implantable devices, neurodevices, neuromorphic hardware, nanotechnology, nanocapsules, drug delivery, botulinum toxin, medical imaging, magnetic resonance imaging, magnetic particle imaging, PET, SPECT, microscopy, brain atlases, cerebral palsy, stroke, Alzheimer's disease, cancer, brain tumors, inflammation, encephalopathy, sleep disorders, ageing, depression, reading disorders, dyslexia, dyscalculia, dysgraphia attention deficiency syndrome, surgery, deep brain stimulation, optogenetics, nursing robots, neuroinflammation, blindness, dysesthesia, neuropathic pain, transcranial Electrical Stimulation (tES), transcranial Direct Current Stimulation (tDCS), transcranial Alternating Current Stimulation (tACS), transcranial Random Noise Stimulation (tRNS) , non-invasive brain stimulation (NIBS),*

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biomechanics, gait, posture, musculoskeletal, joint movement, muscle mechanics, electromyography (EMG), sensors, sensor systems, wearables, robotics, powered prostheses, exoskeletons

Documents by subject area The search resulted in 1,007,103 documents the distribution of which with respect to the subject areas is shown in Figure 28. The most prominent subject area is Medicine which contains 253,790 documents that account for 25.2% of the overall number of documents. Biochemistry Genetics & Molecular Biology ranks second with 123,293 documents, whereas Engineering (84,581 documents) and Neuroscience (35,025 documents) are the other most prominent subject areas.

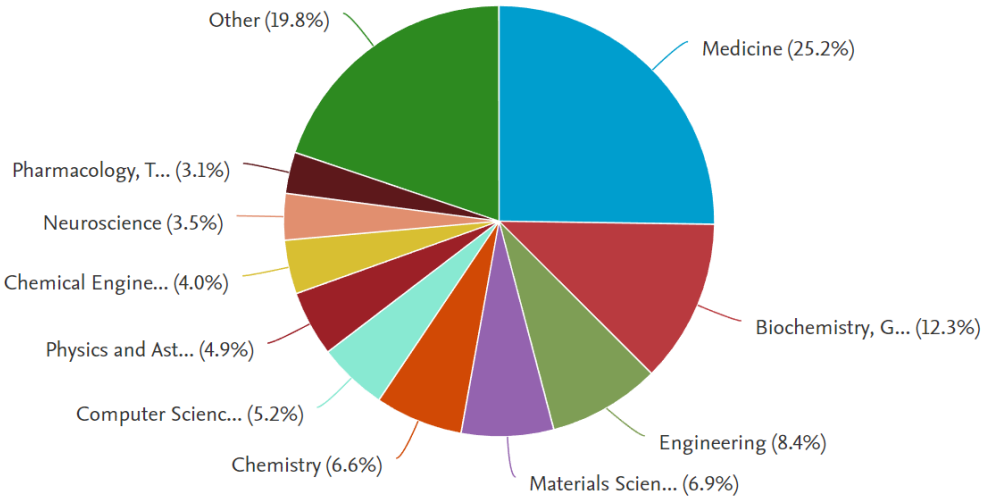

Figure 28. The pie chart illustrates the percentage of subject areas in the field of neuroprosthetics.

Dimension 6 – Subject Area – Medicine

Highlights In Medicine, 253,790 documents and 263,794 author keywords were investigated. Medicine was a challenge-dominant subject area. Figure 29 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge). The key challenges were *anxiety, aging, Alzheimer's disease, mental health, and quality of life*. The key technologies were MRI, biomarker, immunotherapy, radiotherapy, chemotherapy, and deep/machine learning. The most prominent challenges were *cancer, depression, and stroke.*

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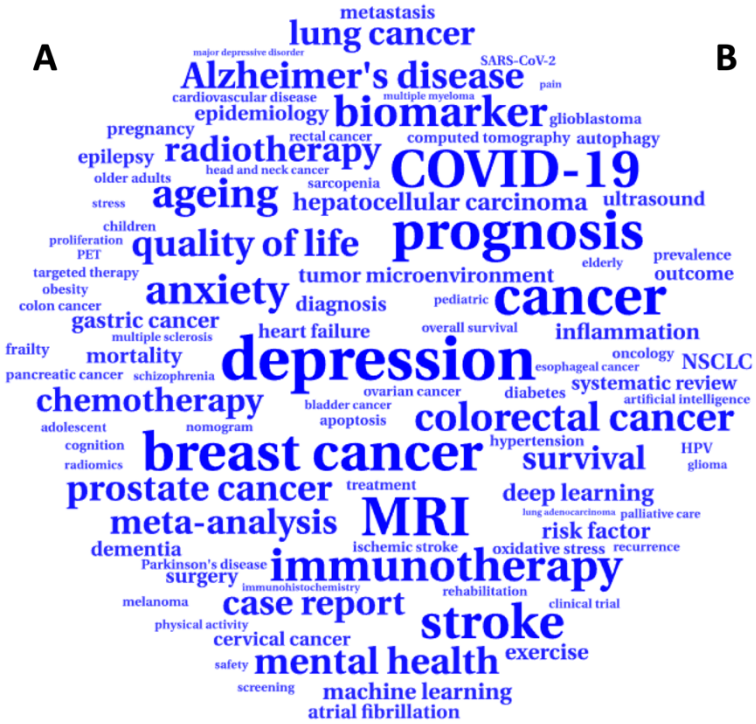
Subject Area: Medicine (253,790 documents, 263,794 author keywords)

A



B

depression	8166
cancer	6549
MRI	6514
prognosis	6440
breast cancer	6380
covid-19	5996
stroke	5156
immunotherapy	4473
biomarker	3974
anxiety	3733
ageing	3585
colorectal cancer	3446
alzheimer's disease	3111
mental health	3106
quality of life	3044
prostate cancer	2993
case report	2761
radiotherapy	2754
meta-analysis	2731
lung cancer	2623
chemotherapy	2618
survival	2582
hepatocellular carcinoma	2573
deep learning	2378
machine learning	2251

Figure 29 Word cloud (A) and the most occurring keywords of Dimension 6 - Subject area – Medicine (B).

Co-occurrence network Figure 30 shows the co-occurrence network in five clusters.

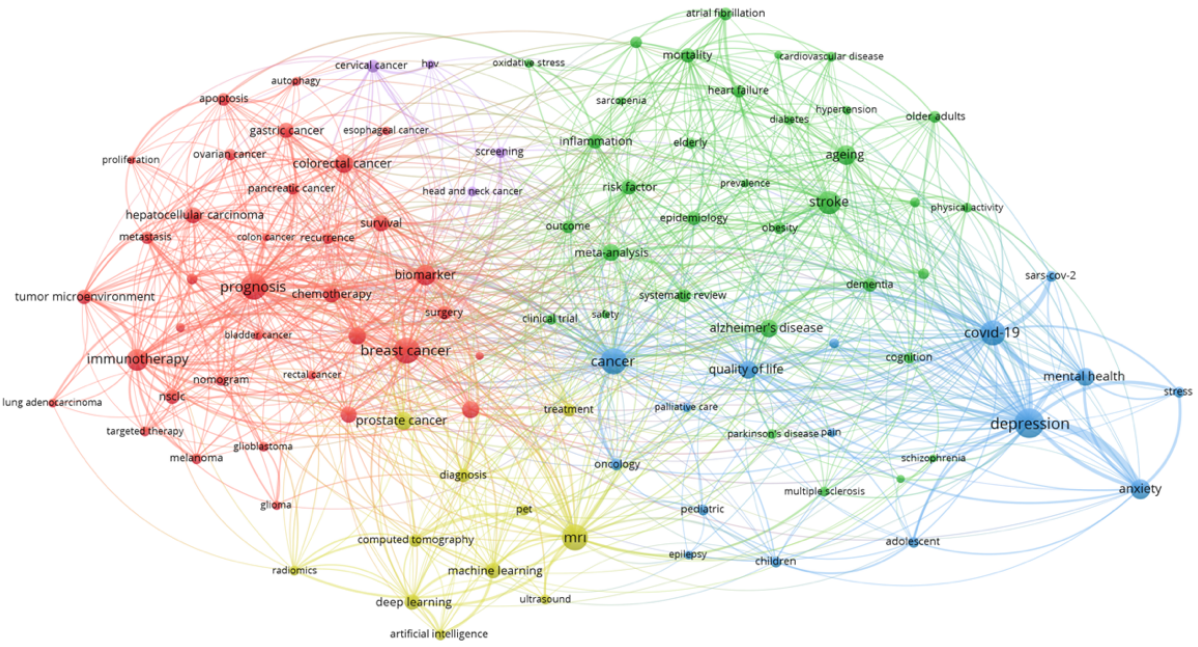


Figure 30. Keyword co-occurrence network based on author keywords of Medicine subject area.

Red cluster

Challenges **Cancer (breast, colorectal, gastric, prostate, hepatocellular carcinoma, pancreatic, colon, ovarian, bladder, glioma, melanoma)**

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Technologies **prognosis, immunotherapy, biomarker, chemotherapy, targeted therapy, surgery, nomogram)**
Challenges **electric vehicle, renewable energy, energy efficiency, climate change, structural health monitoring**

Yellow cluster
Technologies Medical Imaging based **MRI, CT, PET, ultrasound, radiomics**
AI-based **machine learning**, **artificial intelligence**, **deep learning**
Challenges **prostate cancer, diagnosis, treatment**

Green cluster
Challenges **stroke, obesity, heart failure, cardiovascular disease, hypertension, arterial fibrillation, inflammation, Alzheimer's disease, dementia, Parkinson's disease, elderly, MS, schizophrenia, cognition**
Technologies **meta-analysis, epidemiology, systematic review, clinical trial**

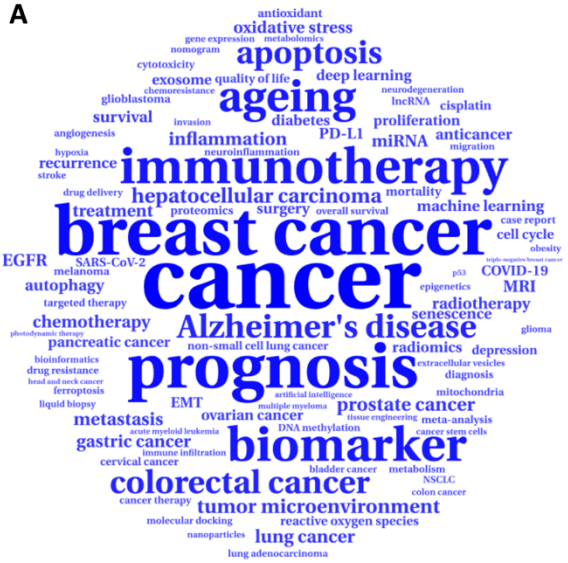
Blue cluster
Challenges **depression, cancer, COVID-19, anxiety, mental health, quality of life, pain, epilepsy**

Dimension 6 – Subject Area - Biochemistry Genetics & Molecular Biology

Highlights In Biochemistry Genetics & Molecular Biology 123,293 documents and 168,134 author keywords were investigated. Biochemistry Genetics & Molecular Biology was challenge-dominant subject area. The most occurring keyword was cancer. Figure 31 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge). Most challenges were cancer-related, however, there were 2 other notable challenges: **aging** and **Alzheimer's disease.** Key technologies were prognosis, immunotherapy, and biomarker**.** The most prominent challenge overall was *cancer***.**

Subject Area: Biochemistry Genetics & Molecular Biology (123,293 documents, 168,134 author keywords)

A



B

cancer	4685
breast cancer	4381
prognosis	3573
immunotherapy	3049
biomarker	2804
ageing	2401
Alzheimer's disease	2276
colorectal cancer	2252
apoptosis	2210
hepatocellular carcinoma	1903
tumor microenvironment	1776
prostate cancer	1613
lung cancer	1479
inflammation	1463
metastasis	1443
gastric cancer	1366
chemotherapy	1308
miRNA	1263
oxidative stress	1229
MRI	1206
radiotherapy	1131
survival	1121
autophagy	1102
machine learning	1045
deep learning	969
ovarian cancer	964
pancreatic cancer	954

Figure 31 Word cloud (A) and the most occurring keywords of Dimension 6 - Subject area – Biochemistry Genetics & Molecular Biology (B).

Co-occurrence network Figure 32 shows the co-occurrence network in five clusters**.**

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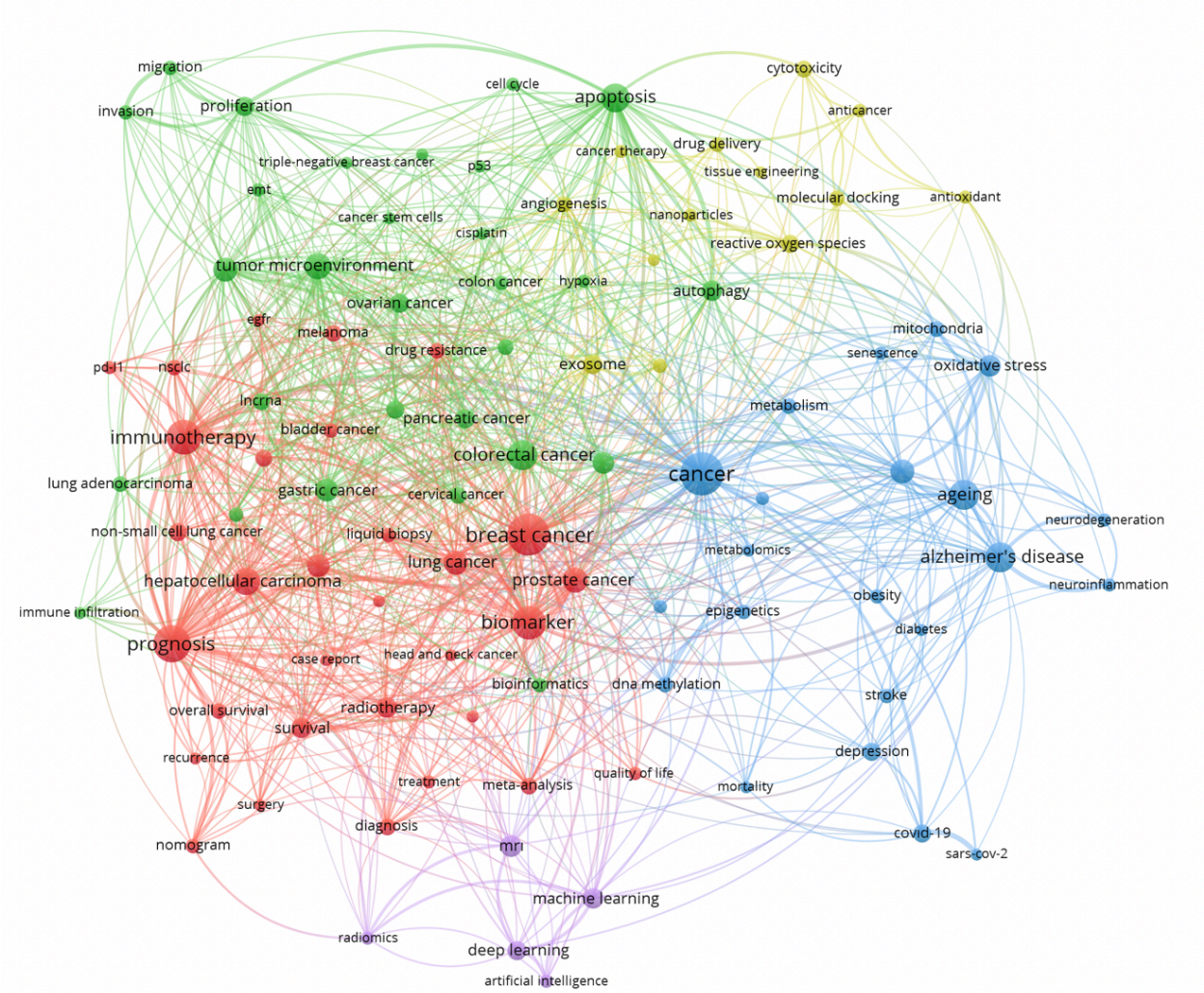

Figure 32. Keyword co-occurrence network based on author keywords of Biochemistry Genetics & Molecular Biology subject area.

Red cluster

Challenges **Cancer (breast, prostate, lung, hepatocellular carcinoma, melanoma, bladder, head and neck, non-small cell lung), drug resistance, quality of life, survival, overall survival, recurrence**

Technologies **prognosis, immunotherapy, biomarker, radiotherapy, diagnosis, treatment, meta-analysis, liquid biopsy, surgery, nomogram, estimated glomerular filtration rate)**

Purple cluster

Technologies **MRI, machine learning, deep learning, artificial intelligence, radiomics**

Yellow cluster

Technologies **exosome, drug delivery, tissue engineering, nanoparticles, reactive oxygen species, angiogenesis, cancer therapy, antioxidant**

Green cluster

Challenges **Cancer (colorectal, pancreatic, gastric, cervical, colon, ovarian, triple-negative breast, lung adenocarcinoma), apoptosis, tumor microenvironment, autophagy, proliferation, migration, invasion, hypoxia**

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Technologies **cisplatin, P53, immune infiltration**

Blue cluster

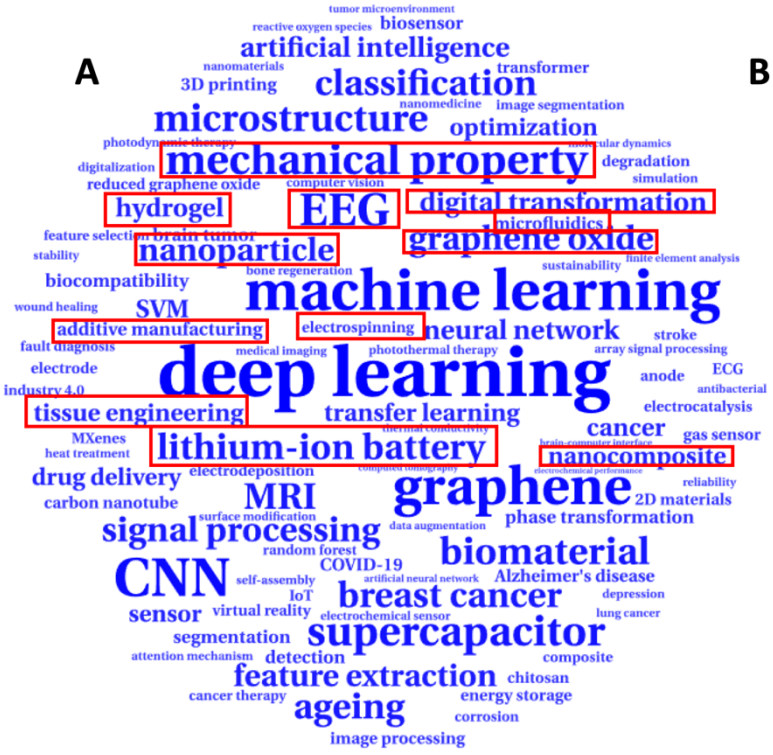
Challenges **cancer, aging, Alzheimer's disease, obesity, diabetes, stroke, depression, neurodegeneration, neuroinflammation, mortality, covid-19, DNA methylation**

Dimension 6 – Subject Area - Engineering

Highlights In Engineering 84,581 documents and 172,963 author keywords were investigated. Engineering was a technology-dominant subject area. The most occurring keyword was deep learning. Figure 33 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge). Dominant technologies were deep/machine learning, CNN, feature extraction, AI, and NN. Other notable technologies were graphene (oxide), EEG, mechanical properties, supercapacitor, biomaterial, lithium-ion battery, nanoparticle, tissue engineering, microfluidics, digital transformation, additive manufacturing, nanocomposite, and hydrogel. Key challenges were *aging and cancer*. The most prominent technologies were AI-based technologies.

Subject Area: Engineering (84,581 documents, 172,963 author keywords)

A



B

deep learning	2690
machine learning	1796
CNN	1578
graphene	1562
EEG	1132
mechanical property	1009
supercapacitor	975
microstructure	808
biomaterial	788
MRI	729
lithium-ion battery	709
classification	707
ageing	702
breast cancer	697
signal processing	651
graphene oxide	630
nanoparticle	572
feature extraction	538
artificial intelligence	530
digital transformation	519
neural network	510
hydrogel	466

Figure 33 Word cloud (A) and the most occurring keywords of Dimension 6 - Subject area – Engineering (B).

Co-occurrence network Figure 34 shows the co-occurrence network in five clusters.

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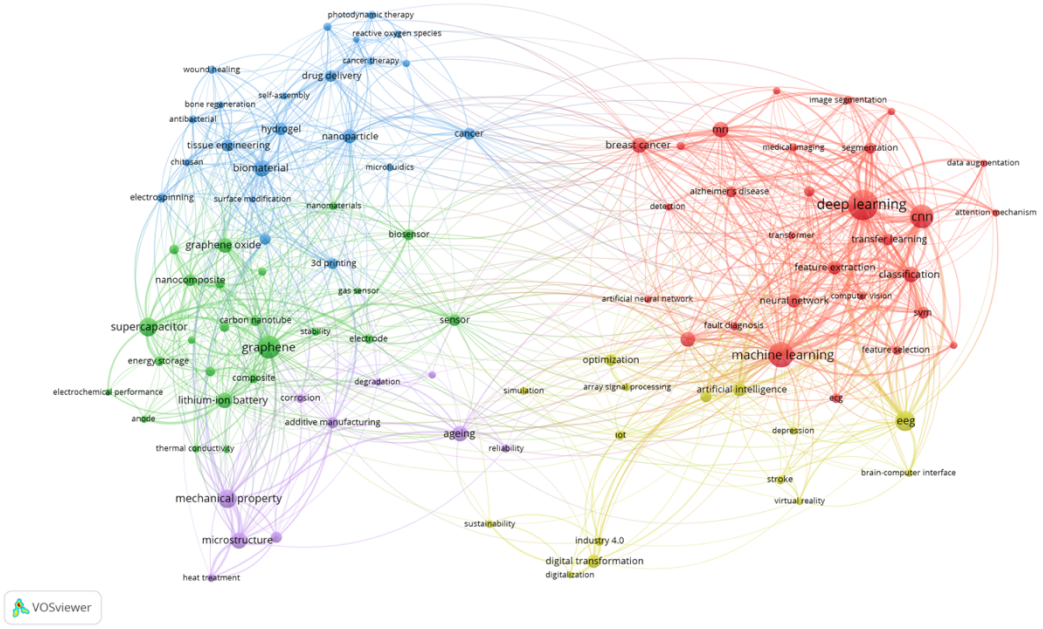

Figure 34. Keyword co-occurrence network based on author keywords of Engineering subject area.

Red cluster

AI-based technologies **deep learning, machine learning, convolutional neural networks, feature extraction, neural network, support vector machine (SVM), transfer learning, feature selection, computer vision, random forest, attention mechanism, artificial neural network**

Medical imaging technologies **MRI, signal processing, segmentation, image processing, ECG, image segmentation, medical imaging, computed tomography**

Challenges **breast cancer, Alzheimer's disease, lung cancer, brain tumor**

Purple cluster

Technologies **mechanical property, microstructure, additive manufacturing, phase transformation, FEM**

Challenges **aging, reliability**

Yellow cluster

Technologies **EEG, artificial intelligence, virtual reality, IoT, digital transformation, optimization, simulation, array signal processing**

Challenges **stroke, sustainability, depression, covid-19**

Green cluster

Technologies **graphene, super capacitor, lithium-ion battery, graphene oxide, nanocomposite, sensor, electrode, carbon nanotube, electrode position, composite, electrochemical sensor, MXenes nanomaterials**

Challenges **energy storage, stability**

Blue cluster

Technologies **biomaterial, nanoparticle, hydrogel, tissue engineering, drug delivery, biocompatibility, 3D printing, electrospinning, photodynamic therapy, microfluidics, surface modification, nanomedicine**

Challenges **cancer, wound healing, bone regeneration, cancer therapy**

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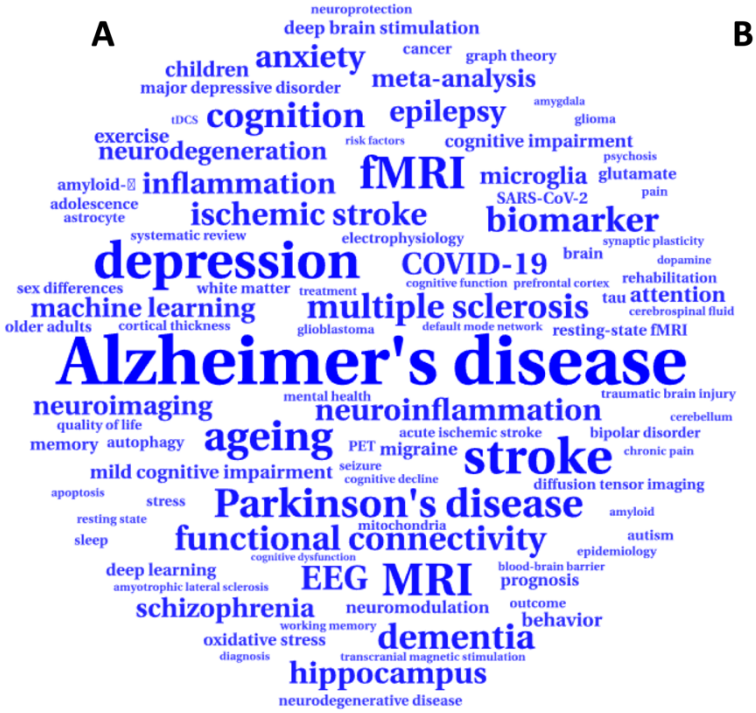
Dimension 6 – Subject Area – Neuroscience

Highlights In Neuroscience 35,025 documents and 54,310 author keywords were investigated. Neuroscience was a challenge-dominant subject area. The most occurring keyword was Alzheimer's disease. Figure 35 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology, yellow: challenge, and blue: other relevant keywords). Key challenges were *depression, stroke, aging, Parkinson's disease, cognition, dementia, and MS*. Key technologies were MRI, fMRI, biomarker, and EEG. The most prominent challenge overall was *Alzheimer's disease.*

Subject Area: Neuroscience (35,025 documents, 54,310 author keywords)

A



B

alzheimer's disease	2778
depression	1591
stroke	1511
MRI	1243
fMRI	1228
ageing	1025
parkinson's disease	961
cognition	737
dementia	728
biomarker	708
multiple sclerosis	688
EEG	681
functional connectivity	681
ischemic stroke	611
anxiety	596
covid-19	559
neuroinflammation	557
hippocampus	551
epilepsy	527
inflammation	521
machine learning	432
neuroimaging	427
schizophrenia	424
neurodegeneration	423

Figure 35 Word cloud (A) and the most occurring keywords of Dimension 6 - Subject area – Neuroscience (B).

Co-occurrence network Figure 36 shows the co-occurrence network in five clusters**.**

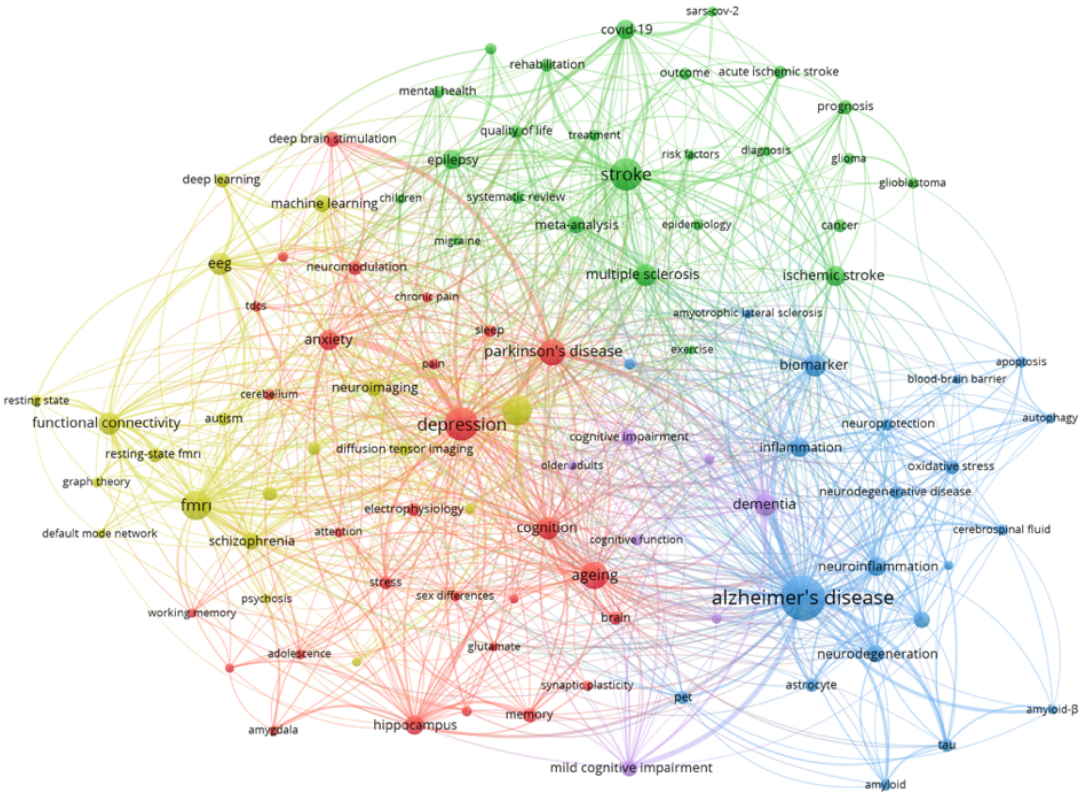


Figure 36. Keyword co-occurrence network based on author keywords of Neuroscience subject area.

Red cluster
Challenges **depression, Parkinson's disease, cognition, aaging anxiety, memory, stress, synaptic plasticity, chronic pain, attention**
Technologies **neuromodulation, deep brain stimulation**

Purple cluster
Challenges **dementia, (mild) cognitive impairment, cognitive function, cognitive decline, older adults**

Yellow cluster
Medical imaging technologies **MRI, fMRI, EEG, neuroimaging, resting state fMRI, Diffusion tensor imaging**
AI-based technologies **machine learning, deep learning**
Challenges **functional connectivity, schizophrenia, major depressive disorder, bipolar disorder, autism, psychosis**

Green cluster
Challenges **stroke, (acute) ischemic stroke, multiple sclerosis, epilepsy, covid-19, cancer, quality of life, mental health, glioma, glioblastoma, migraine**
Technologies **meta-analysis, prognosis, rehabilitation, systematic review, treatment, diagnosis**

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Blue cluster
Challenges **Alzheimer's disease, neurodegeneration, neurodegenerative disease, neuroinflammation, inflammation, apoptosis, traumatic brain injury autophagy**
Technologies **biomarker**

Dimension 7: Clinical Neurotechnology

Definition of the Dimension Specific intervention and monitoring systems need to be integrated into integrated human-in-the-loop digital pipelines for brain health. These loops and pipelines must be designed and aligned with the neurotechnological applications for detection, diagnosis, and intervention, having a major impact on healthcare and representing a separate dimension that needs to be taught and studied. Medium- and long-term objectives must be linked to fundamental challenges in digital brain health, with applications in education and enhancement of cognitive states.

Keywords utilized *depression, inflammation, prognosis, MRI, stroke, biomarker, immunotherapy, surgery, case report, anxiety, quality of life, deep learning, meta-analysis, ageing, colorectal cancer, mental health, risk factor, children, alzheimer's disease, machine learning, prostate cancer, mortality, radiotherapy, apoptosis, survival, chemotherapy, cancer, breast cancer, cervical cancer, pancreatic cancer, ovarian cancer, oncology, hepatocellular carcinoma, obesity, lung cancer, IoT, epidemiology, systematic review, complication, oxidative stress, diagnosis, sensor, sars-cov, gastric cancer, treatment, nsclc, heart failure, CNN, tumor microenvironment, hcc, dementia, rehabilitation, atrial fibrillation, pain, wireless sensor network, metastasis, autophagy, miRNA, adolescent, recurrence, covid-19, older adults, artificial intelligence, computed tomography, neuroinflammation, biomechanics, pregnancy, elderly, ischemic stroke, mechanical property, ultrasound, diabetes, exercise, clinical trial, microstructure, physical activity, cognition, multiple sclerosis, overall survival, nomogram, exosome, pediatric, melanoma, stress, fMRI, screening, cardiovascular disease, hypertension*

Documents by subject area The search resulted in 1,369,117 documents the distribution of which with respect to the subject areas is shown in Figure 37. The most prominent subject area is **Medicine** which contains 375,138 documents that account for 27.4% of the overall number of documents. **Biochemistry Genetics & Molecular Biology** ranks second with 163,324 documents, and **Engineering** ranks the third with 120,070 documents. Notably, **Neuroscience** with 45,840 documents is visible on its own in the pie chart.

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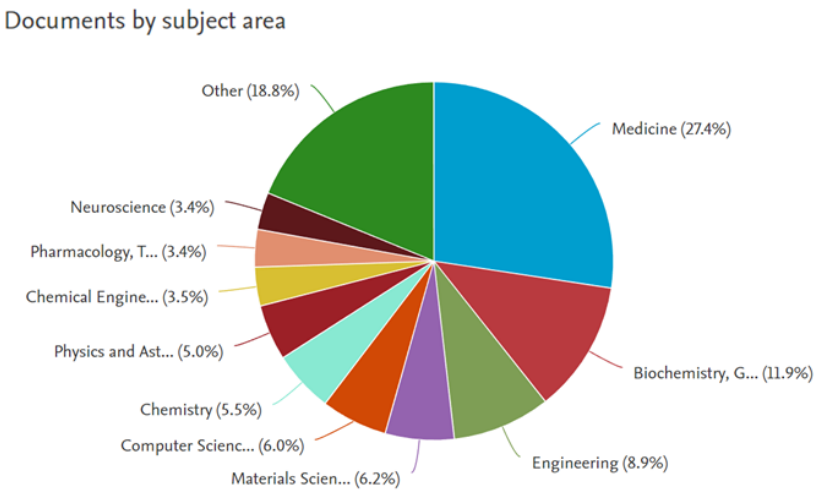


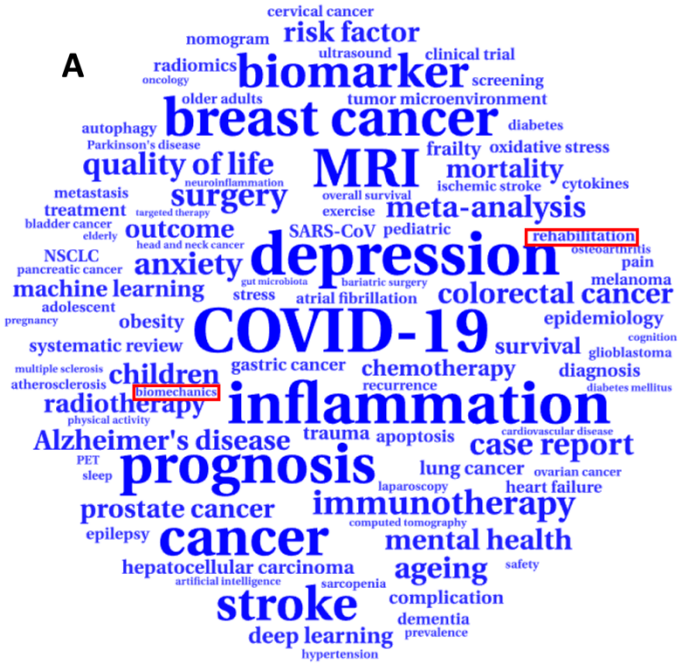
Figure 37. The pie chart illustrates the percentage of subject areas in the field of clinical neurotechnology.

Dimension 7 – Subject Area – Medicine

Highlights In Medicine, 375,138 documents and 375,461 author keywords were investigated. Medicine was a challenge-dominant subject area. The most occurring keyword was depression (following COVID-19). Figure 38 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge). The key technologies were prognosis, MRI, biomarker, and immunotherapy. Notable two other technologies were rehabilitation and biomechanics**.** The most prominent challenges were *COVID-19, depression, inflammation, and cancer.*

Subject Area: Medicine (375,138 documents , 375,461 author keywords)

A



B

covid-19	8749
depression	8166
inflammation	7731
prognosis	6902
MRI	6580
cancer	6549
breast cancer	6381
stroke	5156
biomarker	4839
immunotherapy	4578
surgery	4228
case report	3997
anxiety	3907
quality of life	3841
meta-analysis	3694
ageing	3586
colorectal cancer	3446
mental health	3240
risk factor	3208
children	3151
Alzheimer's disease	3111
prostate cancer	2994
mortality	2885

Figure 38 Word cloud (A) and the most occurring keywords of Dimension 7 - Subject area – Medicine (B)

Co-occurrence network Figure 39 shows the co-occurrence network in five clusters.

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Figure 39. Keyword co-occurrence network based on author keywords of Medicine subject area.

Red cluster

Challenges **cancer (breast, colorectal, prostate, cervical, ovarian, bladder, hepatocellular carcinoma, glioblastoma, melanoma), tumor microenvironment, apoptosis, overall survival, recurrence**

Technologies **prognosis, biomarker, immunotherapy, chemotherapy, radiotherapy, MRI, computed tomography, machine learning, artificial intelligence, screening, radiomics, targeted therapy**

Purple cluster

Techniques **meta-analysis, systematic review**

Yellow cluster

Challenges **COVID-19, depression, anxiety, stress, mental health**

Green cluster

Main Challenge 1 **inflammation, neuroinflammation, Alzheimer's disease, Parkinson's disease, dementia, cognition, aging, pain, sleep, quality of life, osteoarthritis**

Main Challenge 2 **stroke, ischemic stroke, heart failure, cardiovascular disease, arterial fibrillation, obesity, hypertension, prevalence, mortality**

Technologies **biomechanics, rehabilitation**

Blue cluster

Challenges **children, pediatric, adolescent population**, **epilepsy**

Technologies **surgery, case report**

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Dimension 7 – Subject Area - Biochemistry Genetics & Molecular Biology

Highlights In Biochemistry Genetics & Molecular Biology 163,324 documents and 220,160 author keywords were investigated. Biochemistry Genetics & Molecular Biology was challenge-dominant subject area. The most occurring keyword was inflammation. Figure 40 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge). Key technologies were prognosis, biomarker, AI-based technologies, and MRI. Other notable technologies were targeted therapy, drug delivery, nanoparticles, and biomechanics**.** The most prominent challenges were *cancer and inflammation.*

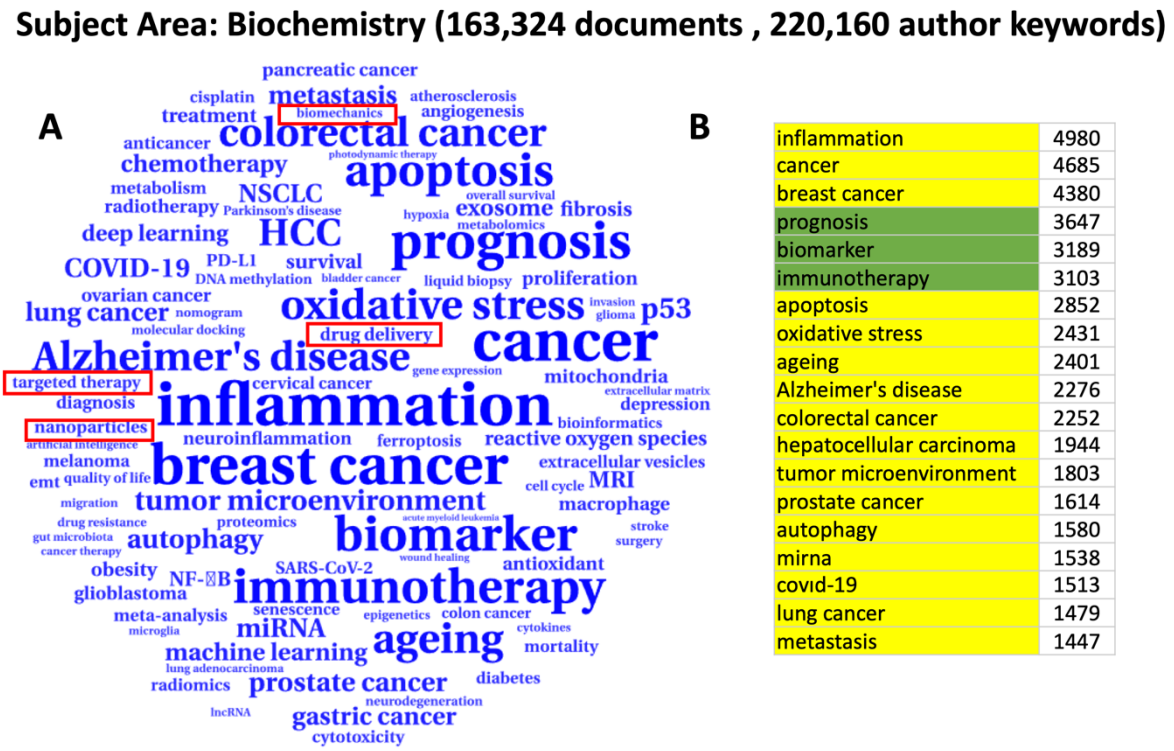

Figure 40 Word cloud (A) and the most occurring keywords of Dimension 7 - Subject area – Biochemistry Genetics & Molecular Biology (B)

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Co-occurrence network Figure 41 shows the co-occurrence network in five clusters.

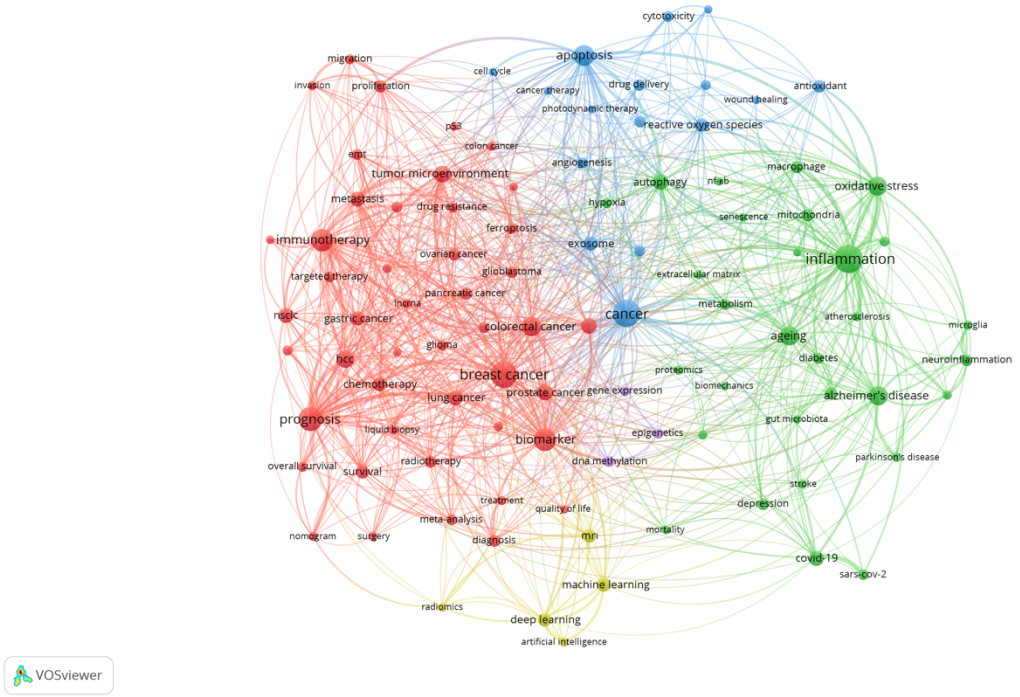

Figure 41. Keyword co-occurrence network based on author keywords of Biochemistry Genetics & Molecular Biology subject area.

Red cluster

Challenges **cancer (breast, colorectal, ovarian, gastric, prostate, lung, pancreatic, hepatocellular carcinoma, glioma, glioblastoma, colon), tumor microenvironment, metastasis, proliferation, migration, invasion, drug resistance, overall survival, quality of life**

Technologies **prognosis, biomarker, immunotherapy, chemotherapy, meta-analysis, radiotherapy, diagnosis, treatment, surgery, targeted therapy**

Yellow cluster

AI-based technologies **deep learning, machine learning, artificial intelligence**

Medical imaging technologies **MRI, radiomics**

Green cluster

Main Challenge **inflammation**

Challenges **oxidative stress, aging, senescence, autophagy, Alzheimer's disease, diabetes, stroke, depression, neuroinflammation, Parkinson's disease, covid-19**

Related keywords **extracellular matrix, metabolism, mitochondria, NF-kB**

Technologies ***biomechanics, proteomics, macrophage***

Blue cluster

Main Challenges **Cancer** and **Apoptosis**

Main relevant keywords **reactive oxygen species, cytotoxicity, apoptosis, angiogenesis, exosomes**

Technologies **photodynamic therapy, drug delivery, wound healing**

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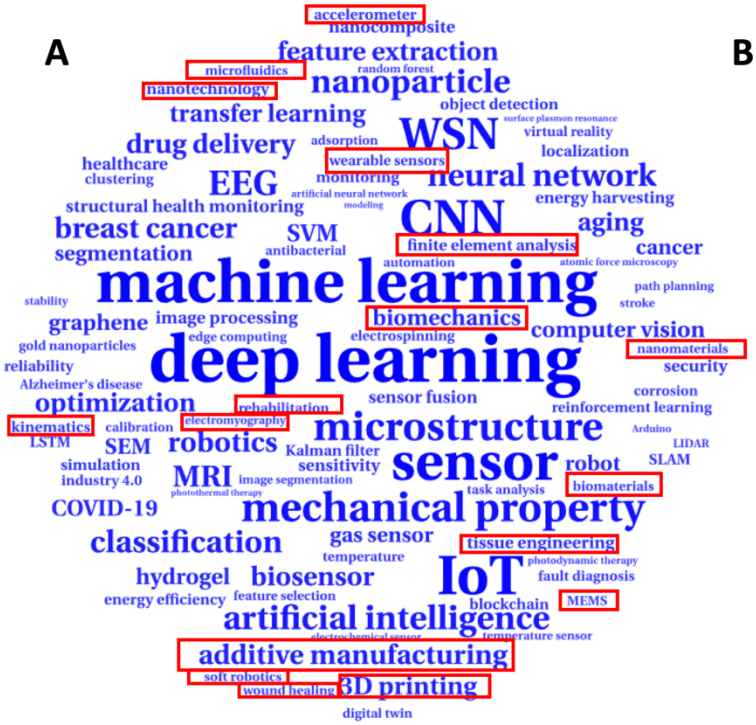
Dimension 7 – Subject Area - Engineering

Highlights In Engineering 120,070 documents and 220,329 author keywords were investigated. Engineering was a technology-dominant subject area. The most occurring keyword was deep learning. Figure 42 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology and yellow: challenge). Key technologies were additive manufacturing and 3D printing. Other notable technologies were biomechanics, kinematics, electromyography, rehabilitation, biomaterials, nanomaterials, wearable sensors, tissue engineering, MEMS, FEA, soft robotics, and wound healing. The most prominent technologies were AI-based technologies, IoT, and sensors.

Subject Area: Engineering (120,070 documents , 220,329 author keywords)

A



B

deep learning	3703
machine learning	3016
IoT	2512
sensor	2415
CNN	1959
wireless sensor networks	1629
mechanical property	1398
microstructure	1360
EEG	1016
artificial intelligence	935
nanoparticle	901
neural network	833
classification	804
MRI	748
breast cancer	701
robotics	671
additive manufacturing	670
drug delivery	643
biosensor	627
feature extraction	602
optimization	601
aging	574
3D printing	557
transfer learning	530

Figure 42 Word cloud (A) and the most occurring keywords of Dimension 7 - Subject area – Engineering (B).

Co-occurrence network Figure 43 shows the co-occurrence network in five clusters.

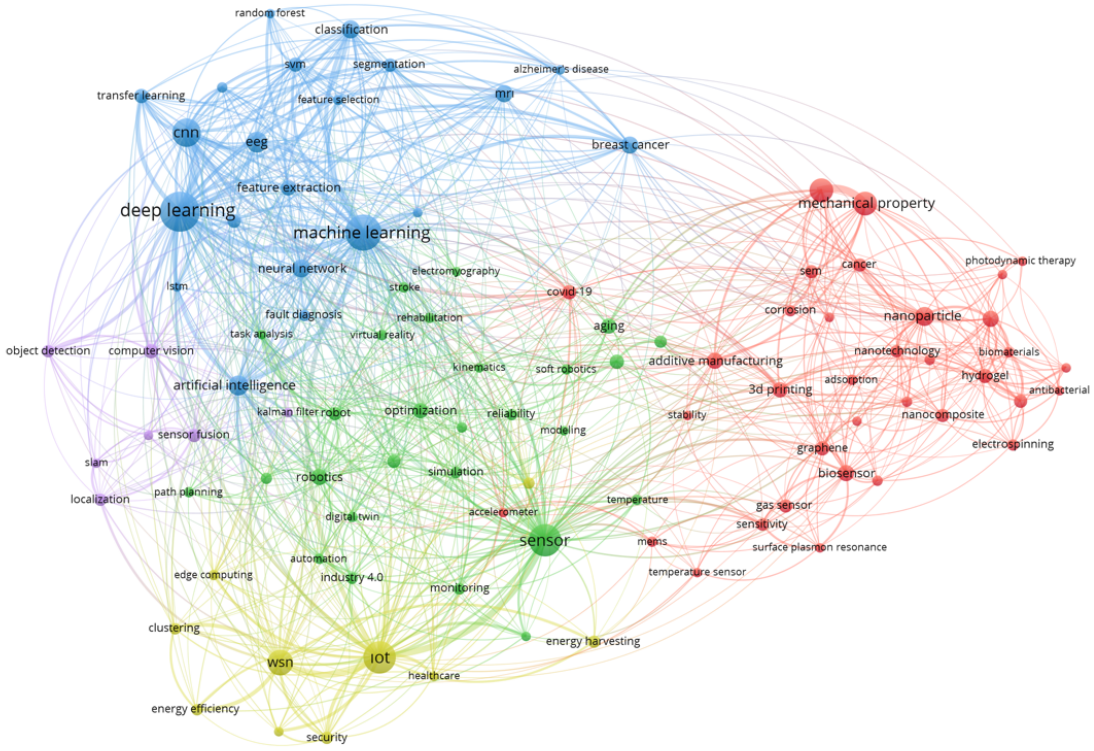


Figure 43. Keyword co-occurrence network based on author keywords of Engineering subject area.

Red cluster

Focus Areas **mechanical property** and **microstructure**

Technologies **nanoparticles, additive manufacturing, 3D, printing, hydrogels, biosensors, scanning Electron microscope (SEM), nanocomposite, nanotechnology, electrospinning, gold nanoparticles, microfluidics, drug delivery, tissue engineering**

Challenges **cancer, wound healing**

Purple cluster

Technologies **object detection, sensor fusion, computer vision**

Yellow cluster

Main Technologies **IoT** and **wireless sensor networks (wsn)**

Technologies **edge computing, clustering, energy efficiency, energy harvesting**

Challenges **security** and **healthcare**

Green cluster

Main Technology **sensors**

Technologies **robotics, optimization, biomechanics, EMG, structural health monitoring, finite element analysis, simulation, monitoring, reinforcement learning, industry 4.0, virtual reality, soft robotics, digital twin**

Challenges **aging, stroke, path planning**

Blue cluster

AI-based technologies **machine learning**, **deep learning**, **neural networks**, **convolutional neural networks**, **support vector machines**, **long-short term memory**, **random forest**, **feature extraction**
Medical Imaging technologies **EEG** and **MRI**
Implications **fault diagnosis, segmentation, image processing**
Challenges **breast cancer** and **Alzheimer's disease**

Dimension 7 – Subject Area – Neuroscience

Highlights In Neuroscience 45,840 documents and 68,529 author keywords were investigated. Neuroscience was a challenge-dominant subject area. The most occurring keyword was Alzheimer's disease. Figure 44 shows word cloud and the occurrence frequencies of keywords with color coding (green: technology, yellow: challenge, and blue: other relevant keywords). Key technologies were MRI, fMRI, EEG, biomarker, functional connectivity, AI-based technologies, deep brain stimulation, and neuromodulation. Other notable technologies were rehabilitation, gait, and DTI. The most prominent challenges were *Alzheimer's disease, depression, stroke, and Parkinson's disease.*

Subject Area: Neuroscience (45,840 documents , 68,529 author keywords)

A

B

alzheimer's disease	2778
depression	1591
stroke	1511
parkinson's disease	1342
MRI	1249
fMRI	1229
EEG	1142
inflammation	1093
ageing	1025
neuroinflammation	1014
multiple sclerosis	861
biomarker	809
cognition	809
dementia	753
epilepsy	729
functional connectivity	713
covid-19	665
microglia	664
anxiety	639
hippocampus	615
ischemic stroke	613
neurodegeneration	524
machine learning	493

Figure 44 Word cloud (A) and the most occurring keywords of Dimension 7 - Subject area – Neuroscience (B).

Co-occurrence network Figure 45 shows the co-occurrence network in five clusters**.**

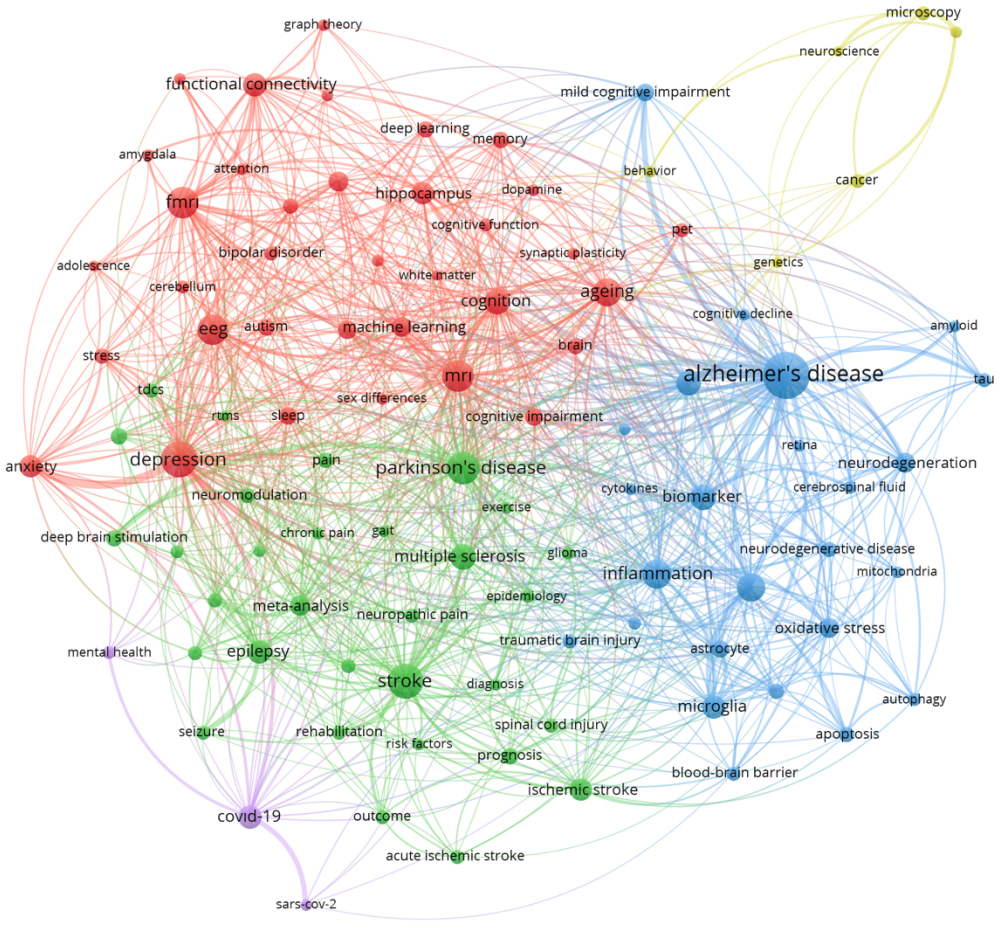


Figure 45. Keyword co-occurrence network based on author keywords of Neuroscience subject area.

Red cluster

Main Challenges **depression, anxiety, aging, cognition**

Challenges **memory, cognitive function, cognitive impairment, schizophrenia, cognitive impairment, autism, stress, sleep, bipolar disorder**

Associated keywords **hippocampus, brain, white matter, dopamine**

Main Technologies **MRI, fMRI, EEG**

Technologies, prediction/solution providing techniques **functional connectivity, machine learning, deep learning, neuroimaging, PET, diffusion tensor imaging**

Yellow cluster

Challenges **cancer, behavior**

Technologies **microscopy, neuroscience**

Green cluster

Challenges **stroke, Parkinson's disease, multiple sclerosis, epilepsy, ischemic stroke, acute ischemic stroke, pain, chronic pain, spinal cord injury, glioma, seizure**

Technologies **meta-analysis, transcranial magnetic stimulation (TMS), deep brain stimulation, neuromodulation, gait, rehabilitation, diagnosis, prognosis**

Blue cluster
Main Challenges **Alzheimer's disease, inflammation, neuroinflammation**
Challenges **Dementia, neurodegeneration, neurodegenerative disease, oxidative stress, mild cognitive impairment, traumatic brain injury, amyotrophic lateral sclerosis (als)**
Associated keywords **microglia, astrocyte, tau, blood-brain barrier, cerebrospinal fluid, mitochondria, retina**
Technologies **biomarker**

Summary

Tables 1-5 show a summary of the bibliometric analyses covering neurotechnology dimensions from 3 to 7 described in detail above. In these tables, the **bold terms** indicate the most prominent, whereas the *italic terms* indicate the less prominent, but potentially impactful technologies and challenges.

Prominent Subject Areas

The analyses from the perspective of subject areas reveal that the subject area which is consistently in the top three with the highest number of academic publications is **Engineering**. Engineering is also the most prominent subject area for three of the neurotechnology dimensions i.e., Dimension 3 (Neuromorphic Systems/Computing), Dimension 4 (Neuromorphic Control/Neurorobotics) and Dimension 5 (Neuroinformatics). **Medicine**, occurring in four of the dimensions in the top three (the exception is Dimension 3 - Neuromorphic Systems/Computing) and being the most prominent in two dimensions (i.e., Dimension 6 - Neuroprosthetics and Dimension 7 - Clinical Neurotechnology) is the next most important subject area. **Computer Science**, occurring in three dimensions in the top three, follows these two subject areas. Other significant subject areas are **Biochemistry**, which occurs in two and **Physics**, which occurs in one dimension in the top three subject areas. Notably, **Neuroscience** does not appear directly in the pie charts for Dimensions 3-5, but can be found in the group referred to as Others. Neuroscience does appear on its own right in the pie charts in Dimensions 6-7, but it is typically among the subject areas with the least number of academic publications. Therefore, the state-of-the-art research globally indicates that neurotechnology has a broader and multi-disciplinary scope, which encompasses neuroscience and is dominated by Engineering and Medicine.

Challenge vs Technology Dominance of Subject Areas

The aforementioned subject areas can be grouped into three main categories:

(1) Technology-dominant For all neurotechnology dimensions, Engineering and Computer Science are consistently technology-dominant (consistently AI-based technologies are the most prominent ones and IoT, medical imaging-based and modeling are also impactful), subject areas. Particularly for Dimension 5 Engineering and Computer Science are focusing primarily on developing technologies for the advancement of technologies, suggesting that relatively less emphasis may be on the underlying challenges. For Dimension 3, both Physics (nanomaterials, nanoparticles and metamaterials) and remarkably also Neuroscience (AI-based and medical imaging-based technologies) are technology-dominant subject areas.

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(2) Challenge-dominant Biochemistry is a challenge dominant subject area for both Dimensions 6 and 7 that it prevails. The main challenge is undoubtedly cancer. For Dimensions 4, 6 and 7 Medicine and Neuroscience are challenge-dominant subject areas, the most studied challenges being stroke, cancer, depression, inflammation, MS and Parkinson's disease for Medicine and Alzheimer's disease, depression, Parkinson's disease and stroke for Neuroscience.

Table 1 Summary of Dimension 3 - Neuromorphic Systems/Computing

	Engineering	Computer Science	Physics	Neuroscience
Technologies	**AI-based** virtual reality, graphene, IoT	**AI-based** virtual reality, IoT, object detection, *task analysis, visualization, computational models, human-centered computing*	**AI-based** nanomaterials, nanoparticles, metamaterials	**AI & medical imaging- based** EEG, MRI, fMRI, *virtual reality, gait, rehabilitation, functional connectivity, eye tracking, neuromodulation, natural language processing*
Challenges	*energy efficiency, optimization, robustness, energy consumption, renewable energy, sustainability, security, robustness, stability, unmanned aerial vehicles, electric vehicles*	*classification, energy efficiency, optimization, robustness, natural language processing, sentiment analysis, forecasting, breast cancer, semantic segmentation*	*classification, energy efficiency, fault diagnosis, object detection, semantic segmentation, defect detection, structural health monitoring, energy efficiency, signal processing, face recognition, security*	Alzheimer's disease, Parkinson's disease, stroke, epilepsy, *decision making, emotion recognition*

(3) Challenge & technology combined For Dimension 5 on the other hand, Medicine and Neuroscience include occurrence of keywords of both technology (medical imaging-based, medical data-based and AI-based technologies) and challenge (Alzheimer's disease, stroke, MS, depression, Parkinson's disease, cancer) nature.

Key technologies

The most prominent technologies utilized across all neurotechnology dimensions are comprised by the hegemonic AI-based technologies. Major architectures like deep learning, machine learning, artificial neural networks, convolutional neural networks and natural language processing models constitute a major portion of the highest-occurring keywords in all subject areas analyzed.

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Table 2 Summary of Dimension 4 - Neuromorphic Control/Neurorobotics

	Engineering	Computer Science	Medicine	Neuroscience
Technologies	**AI-based** IoT, sensor, wireless sensor technologies, *lithium-ion battery, biomechanics, 3D printing*	**AI-based** IoT, sensor, EEG, robotics, virtual reality, augmented reality	**AI-based** MRI, *biomarker, rehabilitation,* meta-analysis, *EEG, biomechanics, electromyography, gait, robotic surgery, neuromodulation*	**Medical imaging** biomarker - Medical imaging: EEG, MRI, fMRI - AI-based: deep learning, machine learning *-Rehabilitation: neuromodulation, motor control, gait, EMG*
Challenges	*electric vehicle, autonomous vehicles, renewable energy, energy storage, energy efficiency, energy harvesting, reliability*	*autonomous vehicle, unmanned aerial vehicles, electric vehicle, energy efficiency, renewable energy, security*	stroke, stroke related conditions, Parkinson's disease, MS, autism	Parkinson's disease, stroke, MS, autism, Alzheimer's disease, *cognition*

These architectures, along with various others like support vector machines, random forest, long short-term memory, and different application methods such as feature extraction, feature selection, and transfer learning especially utilizing u-net, often constitute more than one cluster in various subject areas. The application of AI-based technologies for diagnosing and prognosing medical conditions, along with their ease of use in solving highly nonlinear and complex cases, explains their prevalent presence in neurotechnological dimensions.

Other common technologies that appear across different subject areas can be grouped into seven categories.

(1) Wireless Connectivity Technologies with the Internet of Things (IoT), 5G, 6G, wireless sensor networks, blockchain, edge computing and cloud computing.

(2) Biomedical Imaging-Based Technologies MRI, EEG, fMRI, functional connectivity, neuroimaging, computed tomography, DTI, PET, radiomics.

(3) Medical Data-Based Technologies meta-analysis, systematic review, prognosis, biomarker, diagnosis, case reports.

(4) Modeling-Based & Computational Technologies mathematical/numerical/computational modeling, Finite element modeling, finite element analysis, computational fluid dynamics, optimization, simulation and digital transformation.

(5) Control, Optimization and Robotics Technologies sensors, wireless/wearable sensor technologies, genetic algorithms, sliding mode control, predictive control, optimization, robotics, biomechanics, gait, kinematics, electromyography, EEG, rehabilitation, augmented reality and virtual reality

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(6) Neuromodulation and Neurostimulation Technologies transcranial magnetic stimulation (TMS), repetitive TMS (rTMS), transcranial direct current stimulation (tDCS), deep brain stimulation and graphene.

(7) Biomaterials and Material Science Technologies graphene, graphene oxide, nanotechnology, nanoparticles, nanocomposites, tissue engineering, microfluidics, 3D printing, additive manufacturing, hydrogel, quantum dot.

Table 3 Summary of Dimension 5 - Neuroinformatics

	Engineering	Medicine	Computer Science	Neuroscience
Technologies	**AI-based** - AI-based: deep learning, machine learning, feature extraction - IoT - Modeling based: mathematical/numerical/computational modeling, FEM/FEA, CFD, optimization, simulation - (Medical) imaging based: image processing, visualization, MRI, segmentation - *3D printing, additive manufacturing*	**Medical data based** - Medical data based: meta-analysis, systematic review, prognosis, biomarker, diagnosis - Medical imaging based: MRI, computed tomography, neuroimaging, radiomics, fMRI - AI-based: deep learning, machine learning, artificial intelligence	**AI-based** - AI-based: deep learning, machine learning, feature extraction - IoT - Modeling, computational modeling, optimization - Medical imaging based: image processing, image segmentation, MRI	**Medical imaging based** - Medical imaging based: MRI, fMRI, functional connectivity, neuroimaging, DTI, EEG, PET - *Medical data based: meta-analysis, biomarker, systematic review* - AI-based: machine learning, deep learning
Challenges	electric vehicle, renewable energy, energy efficiency, climate change, structural health monitoring, sustainability, security	**stroke, depression, cancer, Alzheimer's disease, MS**	industry 4.0, social media, cancer, forecasting	**Alzheimer's disease, stroke, MS**

Table 4 Summary of Dimension 6 - Neuroprosthetics

	Medicine	Biochemistry	Engineering	Neuroscience
Technologies	MRI, biomarker, immunotherapy, radiotherapy, chemotherapy, deep/machine learning	prognosis, immunotherapy, biomarker	**AI-based** *graphene (oxide), EEG, mechanical properties, supercapacitor, biomaterial, lithium-ion battery, nanoparticle, tissue engineering, microfluidics, digital transformation, additive manufacturing, nanocomposite, hydrogel*	**Medical imaging** MRI, fMRI, EEG biomarker,
Challenges	cancer, depression, stroke, anxiety, ageing, Alzheimer's disease, mental health, quality of life	Cancer, ageing, Alzheimer's disease	ageing, cancer, *energy storage, stability,* Alzheimer's disease, stroke, *sustainability,* depression	Alzheimer's disease, depression, stroke, ageing, Parkinson's disease, *cognition*, dementia, MS

Table 5 Summary of Dimension 7 - Clinical Neurotechnology

	Medicine	Biochemistry	Engineering	Neuroscience
Technologies	prognosis, MRI, biomarker, immunotherapy, *rehabilitation, biomechanics*	prognosis, biomarker, AI-based technologies, MRI, *targeted therapy, drug delivery, nanoparticles, biomechanics*	AI-based, IoT, sensors additive manufacturing, 3D printing, *biomechanics, kinematics, electromyography, rehabilitation, biomaterials, nanomaterials, wearable sensors, tissue engineering, MEMS, FEA, soft robotics, wound healing*	MRI, fMRI, EEG, biomarker, functional connectivity, AI-based technologies, deep brain stimulation, neuromodulation, *rehabilitation, gait, DTI*
Challenges	Covid-19, depression, inflammation, cancer, stroke, *quality of life*	cancer, inflammation, ageing, Alzheimer's disease	cancer, ageing, Alzheimer's disease, stroke, *security, health care*	Alzheimer's disease, depression, stroke, Parkinson's disease

References

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