

Unveiling the Neurotechnology Landscape: Scientific Advancements Innovations and Major Trends

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Unveiling the Neurotechnology Landscape

Scientific Advancements
Innovations and
Major Trends

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S H O R T S U M M A R Y

Scanning neurotechnology: what is being developed, where and by whom?

Neurotechnology's developments hold profound implications for human identity, autonomy, privacy, behavior, and well-being, i.e. the very essence of what it means to be human.

Since 2013, government investments in this field have exceeded \$6 billion. Private investment has also seen significant growth, with annual funding experiencing a 22-fold increase from 2010 to 2020, reaching \$7.3 billion and totaling \$33.2 billion.

This investment has translated into a 35-fold growth in neuroscience publications between 2000-2021 and 20-fold growth in innovations between 2000-2020, as proxied by patents. However, not all are poised to benefit from such developments, as big divides emerge.

Over 80% of high-impact neuroscience publications are produced by only 10 countries, while 70% of countries contributed fewer than 10 such papers over the period considered. Similarly, six countries only hold 87% of IP5 neurotech patents.



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10 each in 2000-2021

This report targets policy makers, researchers, patent analysts, scientists, technology enthusiasts, ethicists, and anyone interested in the intersection of neuroscience, technology, and society. This report sheds light on the neurotechnology ecosystem, that is, what is being developed, where and by whom, and informs about how neurotechnology interacts with other technological trajectories, especially Artificial Intelligence.

The report underscores the need for evidence in support of policy making and calls for the ethical governance of neurotechnology, to ensure that its development and deployment respects human rights, fundamental freedoms and human dignity, safeguarding individuals and societies.



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"Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed"

Unveiling the **Neurotechnology Landscape**

Scientific Advancements
Innovations and
Major Trends

Foreword

Today we stand at the threshold of a new technological revolution.

Neurotechnology – devices and procedures that seek to access, assess, emulate and act on neural systems – is booming. Driven by new developments in artificial intelligence, it is revolutionizing the way we understand the brain.

This UNESCO report takes stock of this emerging field, by analyzing developments, identifying key actors and highlighting new trends. In doing so, it sheds light on the tremendous promise of neurotechnology, but also the perils it could give rise to.

Indeed, neurotechnology is already leading to breakthroughs, especially in the medical field. Neurostimulation, for example, could allow people with spinal cord injuries to walk again naturally. Deep brain stimulation, where electrodes are inserted into the brain, could help treat conditions like Parkinson's disease and dystonia. The potential of neurotech in the workplace, for example to transcribe our thoughts directly onto computer screens without keyboards, is also being explored.

Yet this potential is not without pitfalls. Deep brain stimulation, for instance, is not only an ally in treating illness. It also has the power to alter individual personalities and behaviours, or change recollections of past events. Never before have humans had the ability to access other minds or manipulate identity. This calls into question fundamental rights like privacy, freedom of thought, free will and human dignity.

This report underlines another key issue: unequal access to this new technology. This risk is already reality: for instance, just six countries have filed almost 90% of the neurotechnology patents registered with leading intellectual property offices worldwide.¹

In this situation, ethical guardrails are needed, so that threats to human rights and dignity are properly addressed, and that the development of neurotechnology benefits everyone. And, for these guardrails to be truly effective, they must be global in scope – because a fragmented approach to this fast-evolving technology is doomed to fail.

¹ The United States account for nearly half of all worldwide patent applications (47%). Other major contributors include South Korea (11%), China (10%), Japan (7%), Germany (7%), and France (5%). This concerns "IP5" intellectual property offices, namely the Chinese National Intellectual Property Administration, CNIPA (formerly SIPO); the European Patent Office, EPO; the Japan Patent Office, JPO; the Korean Intellectual Property Office, KIPO; and the United States Patent and Trademark Office, USPTO



UNESCO has a key role to play in this process. With its mandate in science and universal vocation, UNESCO is unique in its ability to gather governments, experts, scientists, private companies and civil society around the same table to ensure that scientific progress serves, rather than disserves, human dignity.

With this approach, our Organization has long been a frontrunner in the ethics of science and technology. In 1997, our groundbreaking work on the human genome led to the Universal Declaration on the Human Genome and Human Rights. In 2021, our Member States adopted a Recommendation on the Ethics of Artificial Intelligence, the world's first standard-setting instrument in this field – and we are now helping over 40 countries to implement it.

Building on these achievements, UNESCO is contributing to the conversation on the ethics of neurotech. In 2021, our International Bioethics Committee called for a framework to protect the use of neural data – and to defend neurorights. In May 2023, the UNESCO Executive Board responded to this call, by recommending that the 42nd General Conference mandate the Organization to begin drafting a standard-setting instrument on neurotechnology, for adoption in 2025.

This is the global conversation that UNESCO is ready to lead, the conversation we need to have now.

Audrey Azoulay

Director-General
UNESCO

Why Neurotechnology?

The developments that many thought were science fiction only a few years ago are here with us already and are poised to change the very essence of what it means to be human.

While it is heartwarming to see paralyzed people move again thanks to its recent developments, neurotechnology and its ability to interact with the brain, and to monitor and modulate neural activity, can affect our identity, autonomy, privacy, sentiments, behaviors and overall well-being.

The promise to improve the life of those living with disabilities triggered by brain-related problems that neurotechnology makes may come at a high cost in terms of human rights and fundamental freedoms, if abused. This calls for countries to agree on suitable neurotech governance tools and policies, to make sure that neurotech is developed and deployed for the good of individuals, all individuals, and societies worldwide.

Well crafted, effective policies need to rely on hard evidence, and on a clear definition and description of the problem at hand, so that the choices made do not risk being distortive, but rather support the development and use of inclusive and human rights-based technologies. What we need is neurotechnology that is ethical by design.

This is why I think this publication is very important, as it offers first time solid evidence in support of policy making about the scientific advancements, the innovations, the innovators, and the major trends that have been characterizing neurotechnology and its developments over the last two decades. To support future research and analysis, the authors further disclose the full details of the taxonomies proposed, fostering open science.



The fast evolving scientific and technological landscape that emerges, boosted in recent years by increasing investment from both governmental and private actors, does point to a pressing need for an ethical global governance framework for neurotechnology. The measures that a few countries have taken in this respect constitute initial steps towards the global policy response needed to address the transnational nature of research, development, investment, and applications in neurotechnology.

UNESCO has long been leading the ethics of science and new technologies-related debate worldwide, including in relation to the human genome and, more recently, Artificial Intelligence, with its Recommendation on the Ethics of Artificial Intelligence (2021). We have been helping countries translate this normative work into concrete actions, through supporting them building effective institutions and legislations – as we are doing at present in over 40 countries in relation to AI.

We stand ready to support our 194 Member States build a comprehensive governance framework for neurotechnology which puts human rights and fundamental freedoms at the center. At stake is our being human.

Gabriela Ramos

Assistant Director-General for Social and Human Sciences,
UNESCO

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A previous version of this publication has been presented and discussed at various venues, including at the DRUID Conference 2022, as well as workshops with the IKE group at Aalborg University, Denmark, the Department of Business Administration at Göteborg University, Sweden, and the Department of Business Administration at Beijing University of Posts and Telecommunications (BUPT), China.

Executive Summary

Neurotechnology consists of devices and procedures used to access, monitor, investigate, assess, manipulate, and/or emulate the structure and function of the neural systems of animals or human beings. It is poised to revolutionize our understanding of the brain and to unlock innovative solutions to treat a wide range of diseases and disorders.

According to data related to a subset of countries, government investments in neurotechnology have surpassed \$6 billion since 2013, as estimated based on available information. Private investment in neurotech companies has also experienced remarkable growth, with annual funding increasing 22-fold from 2010 to 2020, reaching \$7.3 billion and totaling \$33.2 billion by 2020. Projections point to neurotechnology's growth potential, with the neurotech devices market projected to reach \$24.2 billion by 2027.

Similarly to Artificial Intelligence (AI), and also due to its convergence with AI, neurotechnology may have profound societal and economic impact, beyond the medical realm. As neurotechnology directly relates to the brain, it triggers ethical considerations about fundamental aspects of human existence, including mental integrity, human dignity, personal identity, freedom of thought, autonomy, and privacy. Its potential for enhancement purposes and its accessibility further amplifies its prospect social and societal implications.

The potential impact of neurotechnology has garnered considerable attention by UNESCO Member States. UNESCO's Recommendation on Ethics of AI (2021) urges to consider ethical questions related to AI-enabled neurotechnology systems and brain-computer interfaces, to safeguard human dignity and autonomy. The Recommendation also highlights the potential for AI to manipulate and exploit human cognitive biases and calls for the development of guidelines for human-robot interactions.

The recent discussions held at UNESCO's Executive Board further show Member States' desire to address the ethics and governance of neurotechnology through the elaboration of a new standard-setting instrument on the ethics of neurotechnology, to be adopted in 2025. To this end, it is important to explore the neurotechnology landscape, delineate its boundaries, key players, and trends, and shed light on neurotech's scientific and technological developments.

The present report addresses such a need for evidence in support of policy making in relation to neurotechnology by devising and implementing a novel methodology on data from scientific articles and patents:

- ▶ We detect topics over time and extract relevant keywords using a transformer-based language models fine-tuned for scientific text. Publication data for the period 2000-2021 are sourced from the Scopus database and encompass journal articles and conference proceedings in English. The 2,000 most cited publications per year are further used in in-depth content analysis.
- ▶ Keywords are identified through Named Entity Recognition and used to generate search queries for conducting a semantic search on patents' titles and abstracts, using another language model developed for patent text. This allows us to identify patents associated with the identified neuroscience publications and their topics. The patent data used in the present analysis are sourced from the European Patent Office's Worldwide Patent Statistical Database (PATSTAT). We consider IP5 patents filed between 2000-2020 having an English language abstract and exclude patents solely related to pharmaceuticals.

This approach allows mapping the advancements detailed in scientific literature to the technological applications contained in patent applications, allowing for an analysis of the linkages between science and technology. This almost fully automated novel approach allows repeating the analysis as neurotechnology evolves.

Key stylized facts are:

- ▶ The field of neuroscience has witnessed a remarkable surge in the overall number of publications since 2000, exhibiting a nearly 35-fold increase over the period considered, reaching 1.2 million in 2021. The annual number of publications in neuroscience has nearly tripled since 2000, exceeding 90,000 publications a year in 2021. This increase became even more pronounced since 2019.
- ▶ The United States leads in terms of neuroscience publication output (40%), followed by the United Kingdom (9%), Germany (7%), China (5%), Canada (4%), Japan (4%), Italy (4%), France (4%), the Netherlands (3%), and Australia (3%). These countries account for over 80% of neuroscience publications from 2000 to 2021.
- ▶ Big divides emerge, with 70% of countries in the world having less than 10 high-impact neuroscience publications between 2000 to 2021.
- ▶ Specific neurotechnology-related research trends between 2000 and 2021 include:
 - An increase in Brain-Computer Interface (BCI) research around 2010, maintaining a consistent presence ever since.
 - A significant surge in Epilepsy Detection research in 2017 and 2018, reflecting the increased use of AI and machine learning in healthcare.

- Consistent interest in Neuroimaging Analysis, which peaks around 2004, likely because of its importance in brain activity and language comprehension studies.
 - While peaking in 2016 and 2017, Deep Brain Stimulation (DBS) remains a persistent area of research, underlining its potential in treating conditions like Parkinson's disease and essential tremor.
- Between 2000 and 2020, the total number of patent applications in this field increased significantly, experiencing a 20-fold increase from less than 500 to over 12,000. In terms of annual figures, a consistent upward trend in neurotechnology-related patent applications emerges, with a notable doubling observed between 2015 and 2020.
- The United States account for nearly half of all worldwide patent applications (47%). Other major contributors include South Korea (11%), China (10%), Japan (7%), Germany (7%), and France (5%). These six countries together account for 87% of IP5 neurotech patents applied between 2000 and 2020.
- The United States has historically led the field, with a peak around 2010, a decline towards 2015, and a recovery up to 2020.
 - South Korea emerged as a significant contributor after 1990, overtaking Germany in the late 2000s to become the second-largest developer of neurotechnology. By the late 2010s, South Korea's annual neurotechnology patent applications approximated those of the United States.
 - China exhibits a sharp increase in neurotechnology patent applications in the mid-2010s, bringing it on par with the United States in terms of application numbers.
- The United States ranks highest in both scientific publications and patents, indicating their strong ability to transform knowledge into marketable inventions. China, France, and Korea excel in leveraging knowledge to develop patented innovations. Conversely, countries such as the United Kingdom, Germany, Italy, Canada, Brazil, and Australia lag behind in effectively translating neurotech knowledge into patentable innovations.
- In terms of patent quality measured by forward citations, the leading countries are Germany, US, China, Japan, and Korea.
- A breakdown of patents by technology field reveals that Computer Technology is the most important field in neurotechnology, exceeding Medical Technology, Biotechnology, and Pharmaceuticals. The growing importance of algorithmic applications, including neural computing techniques, also emerges by looking at the increase in patent applications in these fields between 2015-2020. Compared to the reference year, computer technologies-related patents in neurotech increased by 355% and by 92% in medical technology.
- An analysis of the specialization patterns of the top-5 countries developing neurotechnologies reveals that Germany has been specializing in chemistry-related technology fields, whereas Asian countries, particularly South Korea and China, focus on computer science and

electrical engineering-related fields. The United States exhibits a balanced configuration with specializations in both chemistry and computer science-related fields.

- ▶ The entities – i.e. both companies and other institutions – leading worldwide innovation in the neurotech space are: IBM (126 IP5 patents, US), Ping An Technology (105 IP5 patents, CH), Fujitsu (78 IP5 patents, JP), Microsoft (76 IP5 patents, US),² Samsung (72 IP5 patents, KR), Sony (69 IP5 patents JP) and Intel (64 IP5 patents US).

This report further proposes a pioneering taxonomy of neurotechnologies based on International Patent Classification (IPC) codes.

- ▶ Sixty-seven distinct patent clusters in neurotechnology are identified, which mirror the diverse research and development landscape of the field. The 20 most prominent neurotechnology groups, particularly in areas like multimodal neuromodulation, seizure prediction, neuromorphic computing, and brain-computer interfaces, point to potential strategic areas for research and commercialization.
- ▶ The variety of patent clusters identified mirrors the breadth of neurotechnology's potential applications, from medical imaging and limb rehabilitation to sleep optimization and assistive exoskeletons.
- ▶ The development of a baseline IPC-based taxonomy for neurotechnology offers a structured framework that enriches our understanding of this technological space, and can facilitate research, development and analysis. The identified key groups mirror the interdisciplinary nature of neurotechnology and underscores the potential impact of neurotechnology, not only in healthcare but also in areas like information technology and biomaterials, with non-negligible effects over societies and economies.

2 If we consider Microsoft Technology Licensing LLM and Microsoft Corporation as being under the same umbrella, Microsoft leads worldwide developments with 127 IP5 patents. Similarly, if we were to consider that Siemens AG and Siemens Healthcare GmbH belong to the same conglomerate, Siemens would appear much higher in the ranking, in third position, with 84 IP5 patents. The distribution of intellectual property assets across companies belonging to the same conglomerate is frequent and mirrors strategic as well as operational needs and features, among others.

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1.

Introduction

The brain shapes people's identity, autonomy, privacy, sentiments, behaviors and overall well-being, and is intricately intertwined with the very essence of what it means to be human. Neurotechnology, with its ability to interact with the brain, and to monitor and modulate neural activity, promises to improve the life of those living with disabilities triggered by brain-related problems, while at the same time posing important threats to human rights and fundamental freedoms, if abused.

This calls for suitable governance models ensuring that the development, use and deployment of neurotechnology have human rights, fundamental freedoms and human dignity at the center, i.e. for a neurotechnology that is ethical. However, the design and implementation of suitably designed and effective policies and governance approaches requires a clear definition of the problem and on evidence about its main features, trends and determinants.

This report aims to address the need for a better understanding of neurotechnology in support of policy making. It proposes first time evidence about the type of technologies developed, the main innovators in the field, their location as well as the major trends emerged over time, in terms of specific fields in which neurotechnology is unfolding.

Neurotechnology is becoming a major industry, capable of generating substantial economic benefits. Recent estimates suggest that the neurotech devices market may grow at a compounded annual growth rate of 14.4%, going from \$11.3 billion in 2021 to \$24.2 billion in 2027 (BCC Research, 2023). Also, private investment in neurotech companies has also been increasing significantly over time. Between 2010 and 2020, the amount invested in NeuroTech companies increased 22 times, from \$331 million to \$7.3 billion, with total investment in neurotech companies reaching \$33.2 billion by 2020 (NeuroTech ANALYTICS, 2021). This is in addition to government investment in national brain-research initiatives. Rough estimates based on data for a subset of countries, shown in Box 1, suggest that such investment has totaled \$6 billion since 2013.

All this investment translates in scientific and technological advances, which we capture using scientific publications data for the period 2000-2021 and patent data for the period 2000-2020. To this end, we develop and implement a novel deep learning-based approach that extracts neurotechnology-related topics and keywords from relevant scientific literature and exploits the knowledge thus gained to identify neurotechnology innovations from patent application-related data. Specifically, we utilize transformer-based language models, tailored for use with scientific text, to detect coherent topics over time and describe these by relevant keywords that are automatically extracted from a large text corpus. These keywords serve as the foundation for querying and pinpointing neurotechnology in patents, through an approach that leverages the possibilities offered by Artificial Intelligence. The result is a comprehensive map of the technology space, anchored in scientific progression, of the neurotechnology developed over the last two decades.

The analysis based on scientific publications shows that contemporary neuroscience is broad in scope and spans areas such as neurological disorders, neuroimaging, vision studies, artificial intelligence applications in neuroscience, molecular biology, cognitive and neurobehavioral studies, general health-related neurological aspects, and genomics. The United States leads in terms of number of top cited neuroscience developments, followed (at a distance) by the United

Kingdom (9%), Germany (7%), China (5%), Canada (4%), Japan (4%), Italy (4%), France (4%), the Netherlands (3%), and Australia (3%). Overall, these ten countries account over 80% of the most impactful neuroscience knowledge created worldwide, as proxied by top cited scientific publications.

A similarly concentrated patterns emerges in relation to technological innovations in neurotechnology. The United States emerges as the main place where neurotechnology-related innovations are generated (47% of worldwide IP5 patent applications in neurotechnology), followed by Korea (11%), China (10%), Japan (7%), Germany (7%) and France (5%). Overall, these six countries account for 87% of IP5 neurotech patents applied over the period considered.

Over time, we observe a clear shift in the neurotechnology-related developments, whereby computer and medical technologies used in neurotechnology experience a sharp increase in patent applications, as compared to traditionally important technology fields such as biotechnology and pharmaceuticals. China emerges as one of the countries focuses on computer science-related neurotechnology developments, whereas the United States exhibits a hybrid specialization pattern, both chemistry and computer science-related fields to innovate in neurotechnology.

Overall, the picture that emerges is one of sustained but unequal growth and specialization, ignited by massive investment made by both the public and the private sector. These developments are occurring in a context that is generally unregulated and that can therefore lend itself to challenge mental integrity, human dignity, personal identity, freedom of thought, autonomy and privacy, among others. It also raises issues related to accessibility and the potential of using neurotech for enhancement purposes, which may profoundly impact individuals and societies alike. This in turn argues for the need to agree on a common ethical framework, to be able to level the playing field worldwide and to ensure the respect of human rights, fundamental freedoms and human dignity.

In what follows, we first shed light on what neurotechnology is and does, and the ethical concerns it raises (Section 2), to then highlight the data used to identify and characterize neurotechnology-related developments (Section 3). Section 4 synthesizes the innovative approach developed and implemented in order to delineate the boundaries of this complex technology. Key stylized facts based on scientific publication and on patent data are presented in Section 5, before proposing some conclusive remarks in Section 6.

2.

Neurotechnology:
what is it and
what does it do?

The human brain is often referred to as the “input-output” machine of humankind (Driscoll and Neufeld, 2014). With about 100 billion neurons and associated cell types, it has a significance that extends well beyond its physiological functions.

Human beings have consistently endeavored to understand how the brain functions. From ancient practices like trepanning to today’s sophisticated neurotechnology tools and approaches, the quest to shed light on the way the brain works continues, with the aim to identify solutions to physical and mental problems, especially to help those living with disabilities.

Neurotechnology can be defined as the field of devices and procedures used to access, monitor, investigate, assess, manipulate, and/or emulate the structure and function of the neural systems of animals or human beings (UNESCO, 2021). This set of technologies holds significant potential in the treatment of a wide array of diseases and disorders of the nervous system. Whether in the form of devices implanted in neural tissues or wearable devices or else, neurotechnology is opening up new possibilities to help diagnose, treat, and prevent neurological and mental health disorders. In May 2023, groundbreaking research by Lorach *et al.* (2023) revealed a significant achievement in enabling individuals with spinal cord injuries regain the ability to walk naturally by means of using a wireless real-time digital brain-spine interface.

Neurotechnology’s applications however extend well beyond medicine, and span from research, to education, to the workplace, and even people’s everyday life. Neurotechnology-based solutions may enhance learning and skill acquisition, and boost focus through brain stimulation techniques. For instance, early research finds that brain-zapping caps appear to boost memory for at least one month (Berkeley, 2022). This could one day be used at home to enhance memory functions. They can further enable new ways to interact with the many digital devices we use in everyday life, transforming the way we work, live and interact. One example is the Sound Awareness wristband developed by a Stanford team (Neosensory, 2022) which enables individuals to “hear” by converting sound into tactile feedback, so that sound impaired individuals can perceive spoken words through their skin. Takagi and Nishimoto (2023) analyzed the brain scans taken through Magnetic Resonance Imaging (MRI) as individuals were shown thousands of images. They then trained a generative AI tool called Stable Diffusion³ on the brain scan data of the study’s participants, thus creating images that roughly corresponded to the real images shown. While this does not correspond to reading the mind of people, at least not yet, and some limitations of the study have been highlighted (Parshall, 2023), it nevertheless represents an important step towards developing the capability to interface human thoughts with computers, via brain data interpretation.

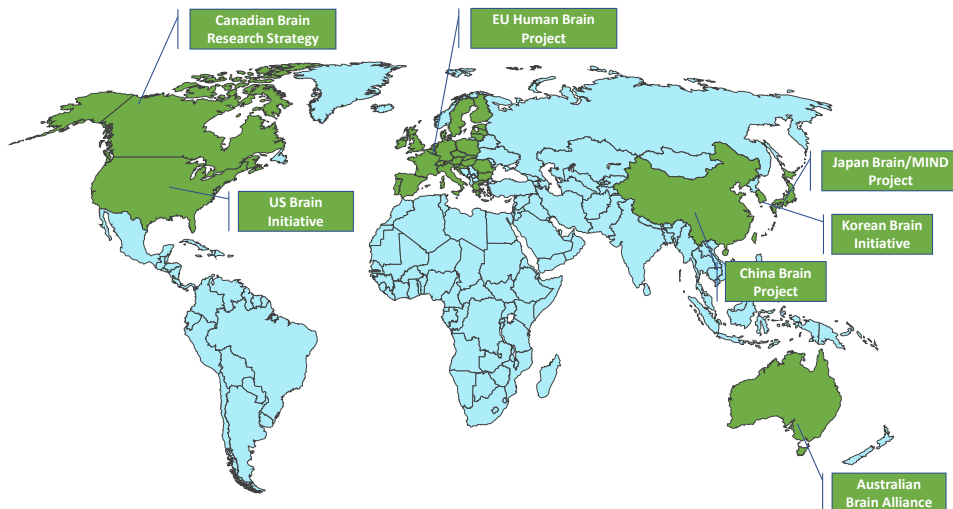
While the above examples may sound somewhat like science fiction, the recent uptake of generative Artificial Intelligence applications and of large language models such as ChatGPT or Bard, demonstrates that the seemingly impossible can quickly become an everyday reality. At present, anyone can purchase online electroencephalogram (EEG) devices for a few hundred dollars, to measure the electrical activity of their brain for meditation, gaming, or other purposes.

3 Stable Diffusion is a deep learning, text-to-image model released in 2022, builds on the work of Rombach *et al.*, (2022). It’s primarily used to generate detailed images conditioned on text descriptions, though it can also be used to generate image-to-image translations guided by a text prompt.

2.1 Growing investments and markets

Thanks to the promises it holds, neurotechnology has garnered significant attention from both governments and the private sector, and is considered by many as an investment priority. According to the International Brain Initiative (IBI), brain research funding has become increasingly important over the past ten years, leading to a rise in large-scale state-led programs aimed at advancing brain intervention technologies (International Brain Initiative, 2021). Since 2013, initiatives such as the United States' Brain Research Through Advancing Innovative Neurotechnologies (BRAIN) Initiative and the European Union's Human Brain Project (HBP), as well as major national initiatives in China, Japan and South Korea have been launched with significant funding support from the respective governments. The Canadian Brain Research Strategy, initially operated as a multi-stakeholder coalition on brain research, is also actively seeking funding support from the government to transform itself into a national research initiative (Canadian Brain Research Strategy, 2022). A similar proposal is also seen in the case of the Australian Brain Alliance, calling for the establishment of an Australian Brain Initiative (Australian Academy of Science, n.d.).

Figure 1. Government-backed and/or national-wide brain research initiatives across the world



Source: adapted from International Brain Initiative (International Brain Initiative, 2023)

These national initiatives aim to unravel the brain's structure and its cognitive processes, to address specific disorders, enhance medical treatments, and provide help to individuals with disabilities (Grillner *et al.*, 2016). Further information about these initiatives is available in Box 1.

BOX 1

Main government-backed and/or national-wide brain-research initiatives

US' BRAIN Initiative (BRAIN)

In April 2013, the United States announced the launch of the Brain Research Through Advancing Innovative Neurotechnologies (BRAIN) Initiative, which aims to accelerate the development and application of new technologies to reveal the dynamic changes of the brain structure and function, investigating how individual brain cells and complex neural circuits interact in time and space.

The BRAIN Initiative is supported by the National Institutes of Health (NIH), which through 2022 has granted over 1,300 awards to numerous investigators, amounting to a total investment of over \$3 billion (US National Institutes of Health, 2023).

Europe's Human Brain Project (HBP)

The Human Brain Project, launched in 2013, is one of the European Future and Emerging Technology Flagship projects. It is co-funded by the European Commission, along with its 123 partners, with a total funding of 607 million euros over the past 10 years (Human Brain Project, 2023).

Initially, the project's focus was on simulating and modeling the brains of mice and humans. It mainly leveraged neurobiology and was organized around six dedicated platforms: neuroinformatic, simulation, high-performance computing, medical informatics, neuromorphic engineering, and robotics.

In its final phase, from April 2020 to September 2023, the Human Brain Project is concentrating on three scientific areas: brain networks, the role of these networks in consciousness, and artificial neural networks. Alongside these research efforts, the project aims to expand the innovative EBRAINS infrastructure⁴, including its tools and services, to further support advancements in brain research.

Japan's Brain/MNDS project (Brain/MNDS)

The Brain Mapping by Integrated Neurotechnology for Disease Studies (Brain/MINDS) program was launched in Japan in 2014 with the aim of comprehensively understanding human brain. This program utilizes a unique non-human primate model to map the neural circuits that contribute to brain structure and function.

⁴ Powered by the EU-cofounded Human Brain Project, EBRAINS provides a digital research infrastructure that accelerates collaborative brain research between leading organizations and researchers across the fields of neuroscience, brain health, and brain-related technologies (Ebrains, 2023).

One notable accomplishment of the Brain/MINDS program is the successful gene mapping project, achieved through in situ hybridization. This technique allows researchers to identify the expression patterns of specific genes within brain tissue. Additionally, the program has introduced various innovative tools and techniques to visualize brain tissue and activity (Grillner et al., 2016).

The Brain/MINDS project had a total budget of 40 billion yen (equivalent to approximately \$365,163,410), which was utilized to support the selected research laboratories and institutions involved in the program. To ensure a diverse range of research proposals, the program invited the public to submit specific proposals in 2013 and 2014. Ultimately, Sixty-five laboratories from 47 institutions were selected to receive funding from the Brain/MINDS program (Okano *et al.*, 2016).

Korean Brain Initiative (KBRI)

On May 30, 2016, the government of Korea unveiled the “Korea Brain Initiative” as part of a 10-year plan aimed to revolutionize brain science through developing neurotechnology and enhancing the neuroscience ecosystem of the country. The Korea Brain Initiative aims to have a pivotal role in the fourth industrial revolution by focusing on understanding high brain function, gaining comprehensive insights into healthy and diseased brains, developing personalized treatments for mental and neurological disorders, and fostering collaboration between scientific institutes, academia, and industry (Korea Brain Research Institute, n.d.).

To support this endeavor, the government planned to invest 1.3 trillion won (equivalent to \$1.2 billion) in basic research in brain science from 2017 to 2022. This investment aimed to secure world-class resources and technology in the field, further bolstering the progress and impact of the Korea Brain Initiative (Choi, 2018).

China Brain Project (CBP)

In 2017, the China Brain Project, also known as the Brain Science and Brain-Inspired Intelligence project, became a scientific and technological initiative included in China’s 13th Five-Year Plan. The project focuses on studying the neural principles of brain cognition and is structured around two components. The first component aims to develop treatments for major brain disorders, by means of conducting research on the neural circuit mechanisms that underlie basic cognitive functions and informing advances on neural circuit mechanisms related to cognition. The second component is dedicated to advancing the development of a new generation of artificial intelligence (AI). This is done through the exploration of brain-inspired technologies, with the aim to enhance the capabilities and performance of AI systems (Yuan *et al.*, 2022)

In the most recent Five-Year Plan approved in 2021 (14th Five-Year Plan 2021-2025), the China Brain Project was allocated a budget of 5 billion yuan (equivalent to approximately \$746 million) and it is likely to receive additional funding in future 5-years plans as well (Dennis, 2022).

Australian Brain Alliance (ABA)

In February 2016, the Australian Brain Alliance (ABA) was established with the support of the Australian Academy of Science and its founding members include the Academy's National Committee on Brain and Mind, the Australasian Neuroscience Society, and the Australian Psychological Society. Over time, the ABA has expanded and currently comprises 28 member organizations, including prominent Australian universities and research institutes that are involved in brain research (Australasian Neuroscience Society, n.d.).

Currently, the Australian Academy of Science is advocating for the establishment of an Australian Brain Initiative with a proposal of \$500 million funding and investment for five-year (Australian Academy of Science, n.d.).

Canadian Brain Research Strategy (CBRS)

While Canada has never had a national brain research initiative, the Canadian Brain Research Strategy (CBRS) has united Canada's brain researchers since 2017, in coalition with indigenous peoples, private and public science funders, industry leaders and people who experienced brain diseases or injuries. The aim is to develop a clear vision about how to advance the study of the brain and translate research outcomes into applications that will benefit human beings.

Significant funding has been provided by the Government to support research on brain health. However, a national brain research initiative has not been established yet. According to the Canadian Institutes of Health Research (CIHR), CIHR invested more than \$212M in dementia research between 2016-17 and 2020-21, including \$49M in 2020-21 alone. In March 2023, a new research investment of \$38.3M was declared by the Government of Canada to support brain health research (Canadian Institutes of Health Research, 2023).

A rough estimate of government investments in this field, relying only on information outlined in Box 1, indicates that more than \$6 billion has been allocated since 2013. In addition to government support, private investment in neurotech companies has also been increasing significantly over time. Between 2010 and 2020, the amount invested in Neurotech companies increased 22 times, from \$331 million to \$7.3 billion, with total investment in neurotech companies reaching \$33.2 billion by 2020 (NeuroTech ANALYTICS, 2021). This surge in private investment may reflect growing market demand and increased adoption of neurotechnology-based solutions. Neurotechnology is expected to become a major industry in the near future, capable of generating substantial economic benefits and projected to reach a value of over \$17 billion by 2026 (Neurotech Reports, 2018). More recent research indicates that the neurotech devices market may grow from \$11.3 billion in 2021 to \$24.2 billion in 2027, at a compound annual growth rate of 14.4% during the period considered (BCC Research, 2023).

2.2 Growing concerns

The rapid advancement of neurotechnology and its applications in many domains trigger a number of important ethical considerations. Unlike other technological innovations, neurotechnology directly interfaces with and exerts influence over the brain, thereby carrying profound implications for fundamental aspects of human existence. These include mental integrity, human dignity, personal identity, freedom of thought, autonomy and privacy, among others. It also raises issues related to accessibility and the potential of using neurotech for enhancement purposes, which may profoundly impact individuals and societies alike (UNESCO, 2021).

Mental integrity is an individual's mastery of her mental states and brain data so that, without the person's consent, no one shall be entitled to read, spread, or alter such states and data, and condition the individual in any way (Lavazza, 2018). An example of the challenges posed to mental integrity relates to the use of Brain-Computer Interfaces (BCIs). BCIs translate brain signals into commands for computers or machines, which can greatly aid those with movement disorders or paralysis. If these devices were to be hacked or manipulated to e.g. alter the individual's intended movements or follow the hacker's commands, this would not only impact the physical autonomy of the person but could also have important psychological effects such as anxiety, depression, or other mental health issues. Doing so would constitute a violation of a person's mental integrity, and of her right to control her own thoughts and actions.

The concept of mental integrity also encompasses the recognition of **human dignity**, including the integrity of the body and the respect of the principle of equality. Article 1 of the Universal Declaration of Human Rights (UDHR) states that "*All human beings are born free and equal in dignity and rights. They are endowed with reason and conscience [...]*" (UN, 1948). In line with this, the integrity of everyone's body, including people's brain and mind as a part of the body, should be recognized, respected and protected from any form of neurotechnological alteration, modification or manipulation as a violation of human dignity (UNESCO, 2021). Neurotechnology further has the potential to impact **personal identity**, which refers to individuals' ability to think and feel for themselves, regardless of how neurotechnology is applied (UNESCO, 2021).

Deep Brain Stimulation (DBS) represents an example of a neuro technology triggering ethical concerns related to both human dignity and personal identity. DBS is a surgical procedure that implants electrodes into specific areas of the brain to regulate abnormal impulses. It is often used to treat conditions like Parkinson's disease, dystonia, or obsessive-compulsive disorder (OCD). However, DBS can also alter an individual's personality or behavior when, for instance, it not only shapes compulsive behaviors as sought, but also reduces desired abilities such as artistic creativity. DBS techniques can also alter a patient's recollection of past events and do so in different ways. In such cases, people's human dignity and personal identity, that is the essence that made them unique, can be infringed, as the active presence of the technical device in the brain can disrupt the coherence of a patient's mind and threaten one's authentic self.

The Increasing possibilities offered by neurotechnology-related developments, including monitoring, surveillance, and manipulation of cognitive functions, can potentially interfere with cognitive processes, particularly in relation to free and competent decision-making. This is central to **autonomy**, which refers to a person's capacity to engage in self-directed actions

that fulfill the criteria of intentionality and awareness, free from external influences aimed at controlling or determining the person's actions (Beauchamp and Childress, 2001). Autonomy is closely intertwined with the concept of **informed consent**. In this respect, article 6 of the Universal Declaration on Bioethics and Human Rights (UDBHR) states that any preventive, diagnostic and therapeutic medical intervention as well as scientific research should only be carried out "with the prior, free, express and informed consent of the person concerned" (UNESCO, 2005). In the case of neurotechnology, additional challenges arise in relation to the applicability of the informed consent principle, since the risks and benefits associated to the use of these technologies are still to be fully assessed and relevant information is at time partial or unavailable.

Ethical concerns related to autonomy and informed consent for example may be triggered by neuroimaging techniques, such as functional Magnetic Resonance Imaging (fMRI). Neuroimaging has the potential to identify individual thought patterns or even predict behaviors. For instance, employers could use neuroimaging techniques to assess the suitability of potential job candidates, arguing that it helps choose the most qualified or suitable individuals. However, this would raise ethical questions related to candidates understanding or not the implications of what their brain scans might reveal, or being unaware of the potential misuse of this data (e.g. being unfairly judged on qualities irrelevant to the job, or revealing deep personal information, such as susceptibility to certain mental illnesses). In such cases, the validity of informed consent gets undermined. Furthermore, and given the typical imbalances that exist in bargaining power between employers and employees, individuals may feel obliged to test, and therefore see their autonomy, i.e. their ability to make free and uncoerced decisions about their own lives is impaired.

As neurotechnology may record and transmit brain data as well as digital information pertaining to brain activity, it may also intrude into **mental privacy**. The latter refers to the explicit protection of individuals against the unconsented intrusion by third parties into their mental information as well as against the unauthorized collection of personal data (Ienca and Andorno, 2017). Personal brain data, also known as neural data, is data relating to the functioning or structure of the human brain of an identified or identifiable individual that includes unique information about their physiology, health, or mental states (OECD, 2019). Individuals generate a significant portion of neural data unconsciously, meaning that through neurotechnology individuals may unknowingly or unintentionally share information they would not otherwise disclose (UNESCO, 2021). The collection and processing of data from neurodevices could be used to identify individuals or reveal their brain activity, particularly in relation to stigmatizing neurological or mental health conditions, thus potentially leading to discriminatory practices (Kostiuk, 2012).

Beyond the medical realm, research suggests that emotional responses of consumers related to preferences and risks can be concurrently tracked by neurotechnology, such as neuroimaging and that neural data can better predict market-level outcomes than traditional behavioral data (Karmarkar and Yoon, 2016). As such, neural data is increasingly sought after in the consumer

market for purposes such as digital phenotyping,⁵ neurogaming,⁶ and neuromarketing⁷ (UNESCO, 2021). This surge in demand gives rise to risks like hacking, unauthorized data reuse, extraction of privacy-sensitive information, digital surveillance, criminal exploitation of data, and other forms of abuse. These risks prompt the question of whether **neural data** needs distinct definition and safeguarding measures.

These issues are particularly relevant today as a wide range of electroencephalogram (EEG) headsets that can be used at home are now available in consumer markets for purposes that range from meditation assistance to controlling electronic devices through the mind. Imagine an individual is using one of these devices to play a neurofeedback game, which records the person's brain waves during the game. Without the person being aware, the system can also identify the patterns associated with an undiagnosed mental health condition, such as anxiety. If the game company sells this data to third parties, e.g. health insurance providers, this may lead to an increase of insurance fees based on undisclosed information. This hypothetical situation would represent a clear violation of mental privacy and of unethical use of neural data.

Another example is in the field of advertising, where companies are increasingly interested in using neuroimaging to better understand consumers' responses to their products or advertisements, a practice known as neuromarketing. For instance, a company might use neural data to determine which advertisements elicit the most positive emotional responses in consumers. While this can help companies improve their marketing strategies, it raises significant concerns about mental privacy. Questions arise in relation to consumers being aware or not that their neural data is being used, and in the extent to which this can lead to manipulative advertising practices that unfairly exploit unconscious preferences. Such potential abuses underscore the need for explicit consent and rigorous data protection measures in the use of neurotechnology for neuromarketing purposes.

Ethical concerns also arise in relation to the accessibility of neurotechnology and the implications for **social justice**, especially when neurotechnology initially developed for patients with disorders are employed by healthy individuals for **enhancement** purposes. For instance, cognitive abilities could be enhanced through the development and distribution of neuro-enhancement devices, such as transcranial Direct-Current Stimulation (tDCS) units. Suppose such a product enhancing memory or attention becomes available on consumer markets, but at high cost, thus making only wealthy individuals able to afford it. This situation could exacerbate existing social inequalities, with privileged groups gaining further advantages in academic or professional fields where enhanced cognitive abilities could provide a competitive edge.

5 Digital phenotyping is defined as the 'moment-by-moment quantification of the individual-level human phenotype in situ using data from personal digital devices' (Onnela and Rauch, 2016).

6 Neurogaming is a novel form of gaming that involves the use of brain-computer interfaces such as EEG helmets so that users can interact with the game without use of a traditional controller (UNESCO, 2021).

7 Neuromarketing is an interdisciplinary field of science that uses various tools traditionally used in medicine, psychiatry and psychology on neurofeedback, biofeedback and metabolic processes measures, in conjunction with traditional marketing tools in the search to better understand the most diverse types of emotions, cognitions, physiological reactions, behaviors and thoughts of economic agents, both conscious and unconscious related to typical issues of Marketing and its various sub-areas (de Oliveira and Giraldi, 2017)

The impact of these technologies on **vulnerable populations**, including **children** and **adolescents**, warrants special consideration. Children and adolescents, given their ongoing neurodevelopment and the plasticity of their brains (Spear, 2013), are more susceptible to the potential side effects or unintended consequences of neurotechnology. If a school were to introduce a program where students use Brain-Computer Interfaces (BCIs) to improve their learning, this could potentially enhance educational outcomes, while nevertheless posing a number of ethical challenges. On the one hand, the excessive reliance on BCIs for learning might negatively impact students' other essential cognitive skills, including creativity or problem-solving. On the other hand, the integration of neurodevices and brain-computer interfaces during crucial periods of neurodevelopment may make it challenging to distinguish between character traits and behaviors that can be attributed to the neurodevice itself as compared to those that arise from the "normal" maturation of the brain.

2.3 The emerging neurorights-related debate

In the face of these challenges, in recent years some scientists and neuro-ethicists have proposed the concept of "neurorights" to address the ethical and legal challenges associated with the development of neurotechnology (Ienca and Andorno, 2017; Lavazza, 2018; Ienca, 2021; Yuste, Genser and Herrmann, 2021). Proponents of "neurorights" call for "a new international legal and human rights framework [...] that can be understood as a new set of human rights for the brain" (Yuste, Genser and Herrmann, 2021). The introduction of "neuroright" aims to offer individuals enhanced legal safeguards that go beyond current laws and regulations.

The question around implementing such rights has sparked a vivid discussion among experts, in relation to a wide array of concerns ranging from apprehension about the potential erosion of established human rights to the practical complexities of formulating and enforcing such novel rights.

One major point of contention revolves around the potential impact of introducing new rights on existing human rights frameworks. Critics argue that the introduction of neurorights might dilute or overshadow the fundamental rights already in place, leading to a fragmented or weakened human rights system (Rommelfanger, Pustilnik and Salles, 2022). Some experts further argue that providing specific protections for neurotechnological advancements may not be needed as well-established human rights instruments already encompass many of the concerns associated with these advancements (Borbón and Borbón, 2021; Zúñiga-Fajuri *et al.*, 2021).

Those discussing the practical challenges associated with defining and implementing "neurorights" basically argue that, given the rapidly evolving nature of neurotechnology and its wide-ranging applications, it is very challenging to devise a comprehensive and coherent set of relevant rights. Experts question the feasibility of establishing clear and enforceable rights that adequately address the intricate ethical, social, and legal dimensions of neurotechnology (Bublitz, 2022). Additionally, people's interpretation of "neurorights" are shaped by their specific cultural, economic and political contexts, as well as the frameworks they use to regulate them, hence creating another implementation obstacle (Herrera-Ferrá *et al.*, 2022; Arleen, 2023).

BOX 2

UNESCO International Bioethics Committee's position on “Neurorights” (UNESCO, 2021)

The International Bioethics Committee (IBC), which is an expert advisory body of UNESCO, considers that “neurorights” embrace certain human rights that are already recognized in national laws, international law, and international human rights instruments. These rights rest on the recognition of the basic rights of all individuals to physical and mental integrity, mental privacy, freedom of thought and free will, and the right to enjoy the benefits of scientific progress, and on the recognition of the need to protect and promote these rights with regard to the application of neurotechnology. They also include the right to decide freely and responsibly on matters related to the use of neurotechnology, without any form of discrimination, coercion or violence.”

The IBC further calls on the UNESCO to use its unique mandate on bioethics and on the ethics of science and technology to lead the global efforts on the ethics of neuroscience and neurotechnology, to identify the gaps in existing legal frameworks, and to advance the elaboration of a standard-setting instrument in this domain.

2.4 The need to address the international governance vacuum

Irrespective of position taken by the experts in the ongoing debate about the need for neuro-specific human rights, consensus exists about the need to protect and promote human rights. A comprehensive global ethical framework that can offer guidance to national policies and regulations aimed at safeguarding individual's rights and freedoms in relation to neurotechnology, particularly in non-medical contexts, emerges as something that is urgently needed.

At the national level, only a few countries have enacted laws and regulations to protect mental integrity or have included neuro-data in personal data protection laws (UNESCO, University of Milan-Bicocca (Italy) and State University of New York – Downstate Health Sciences University, 2023). Examples are the constitutional reform undertaken by Chile (Republic of Chile, 2021), the Charter for the responsible development of neurotechnologies of the Government of France (Government of France, 2022), and the Digital Rights Charter of the Government of Spain (Government of Spain, 2021). They propose different approaches to the regulation and protection of human rights in relation to neurotechnology. Countries such as the UK are also examining under which circumstances neural data may be considered as a special category of data under the general data protection framework (i.e. UK's GDPR) (UK's Information Commissioner's Office, 2023).

At the international level, several organizations have started to discuss the ethical, legal and societal concerns related to neurotechnology. The Organization for Economic Cooperation and Development (OECD) approved a “Recommendation on Responsible Innovation in Neurotechnology” in 2019, which anticipates certain challenges posed by neurotechnologies from the lens of responsible innovation in the context of health-oriented applications (OECD, 2019). The Council of Europe has held discussions on the topic from a human rights perspective (Council of Europe, 2021), whereas the Organization of American States (OAS) has adopted the Inter-American declaration of principles regarding neuroscience, neurotechnologies, and human rights (Organization of American States, 2023). While these efforts represent a much-needed contribution to addressing the challenges triggered by neurotechnology, they each address a part of the problem and are thus unable to provide a wholistic approach to it.

In September 2020, UN Member States called upon the Secretary-General to prepare recommendations that would advance the “common agenda” of all countries and respond to current and future challenges to humanity (A/RES/75/1) (UN, 2020). These included digital technologies and their ability to fuel divisions within and between countries, increase insecurity, undermine human rights, and exacerbate inequalities. In September 2021, the United Nations Secretary-General responded with the “Our Common Agenda” report, which included neurotechnology as a frontier human rights issue requiring clarifications in relation to applicable human rights frameworks and standards, with the aim to prevent harm in the digital or technology spaces (UN, 2021). In this vein, the Human Rights Council has requested its Advisory Committee at its 51st Session to produce a report on the impact, opportunities and challenges of neurotechnology vis-a-vis the promotion and protection of all human rights (Resolution A/HRC/51/L.3). This report analyzing the human rights implications of neurotechnology will be submitted to the Human Rights Council at its 57th session in September 2024 (Human Rights Council, 2022).

BOX 3

UNESCO's work on the ethics of neurotechnology

UNESCO has played a significant role within the United Nations (UN) system in the field of neurotechnology, leveraging its mandate and expertise in bioethics, the ethics of science and technology, and its pioneering work related to the governance of emerging and converging technologies. The 2021 report published by UNESCO's IBC represents the most extensive review to date on the ethical, legal, and social implications of neurotechnology and contains concrete recommendations about the possible way forward (UNESCO, 2021).

In addition to steering the international and the UN system debate on the issue, UNESCO has been raising public awareness and advocating for policy efforts in relation to neurotechnology. A report on the risks and challenges of neurotechnology for human rights was published by UNESCO in December 2022 (UNESCO, University of Milan-Bicocca (Italy) and State University of New York – Downstate Health Sciences University, 2023), in collaboration with Milano-Bicocca University and SUNY Downstate Health Sciences University. The present report on the global neurotechnology landscape aims to contribute to this endeavor, by providing hard evidence about the key actors in the field, what they are developing and where key advances are taking place.

In May 2023, the 216th Executive Board of UNESCO recommended that the 42nd General Conference grant the Organization the mandate to develop a global standard-setting instrument on the ethics of neurotechnology (UNESCO, 2023). If approved by UNESCO Member States in November 2023 at the 42nd General Conference, this standard-setting instrument is expected to comprehensively address the ethical challenges arising from the field of neurotechnology and propose a governance model to effectively tackle them, to protect and promote human rights and fundamental freedoms.

2.5 Understanding the neurotechnology landscape to inform the policy debate

As it happens in the case of other pathbreaking technologies (see e.g. Baruffaldi et al., 2020 in relation to Artificial Intelligence) drawing the boundaries of neurotechnology is an inherently complex task. Neurotechnology stems from the intersection of several disciplines, including neuroscience, chemistry, bioengineering, computer science, materials science, and medical technology. Neurotechnology encompasses not only the direct recording of human brain activity and the direct influence or modification of brain activity but extends to encompassing any device or application, including apps, AI, and big data, that can derive knowledge from an individual's brain activity or influence and modify it.

While having a comprehensive understanding of the neurotechnology landscape represents a non-trivial task, also in light of the broad scope and range of neurotechnology applications, it is a necessary one. Designing and implementing effective targeted policies needs relying on an accurate definition of the problem at hand. This calls for the identification and measurement of the advancements occurred in the field, around the world and over time. It also requires a thorough assessment of the main scientific and technological trajectories that characterize neurotechnology, for governance and oversight models to be adequate and effective.

This is why this report proposes first time evidence about the type of technologies developed, the main innovators in the field, their location as well as the major trends emerged over time. This is achieved through devising a novel deep learning-based approach that extracts neurotechnology-related topics and keywords from relevant scientific literature and exploits the knowledge thus gained to identify neurotechnology innovations from patent application-related data. Specifically, we utilize transformer-based language models, tailored for use with scientific text, to detect coherent topics over time and describe these by relevant keywords that are automatically extracted from a large text corpus. These keywords serve as the foundation for querying and pinpointing neurotechnology patents, resulting in a comprehensive map of the technology space, anchored in scientific progression.

Thanks to the evidence thus generated, this report aims to contribute to a better understanding of the state-of-the-art of the global neurotechnology landscape to inform the policy debate towards an international ethical framework for neurotech governance.

3.

Identifying
and characterizing
neurotechnology
developments: the data

To identify applications of neurotechnology and propose a first-time picture of the neurotechnology landscape, we harness large data corpora, encompassing both publication and patent documents. We use data contained in the Scopus database about neuroscience-related publications and patent document-related information contained in the European Patent Office's Worldwide Patent Statistical Database (PATSTAT). The study covers more than two decades, i.e. the period 2000-2021, to capture the evolution of neurotechnology over time.

Looking at scientific publications and patents allows us to shed light on both scientific developments, through publications (Sternitzke, 2009; Mingers and Leydesdorff, 2015) and on technological applications, from patent documents (Griliches, 1992; Mattes, Stacey and Marinova, 2006; Igami and Subrahmanyam, 2019) and, to uncover the science- innovation links that underpin the development of new technological trajectories like neurotechnology. The first-time characterization proposed in the present report not only sheds light on key trends and leading innovators worldwide. It also uncovers the main themes or subfields that compose the neurotechnology universe, thereby contributing significantly to the informed-policy discourse around neurotechnology governance.

More details about the type of data used in the study as well as about the innovative identification strategy devised for the study can be found in Hain, Jurowetzki and Squicciarini (2022) and Bekamiri, Hain and Jurowetzki (2021). In the present report we limit ourselves to provide some basic elements related to the data and the operational strategy devised to identify and characterize developments in neurotechnology, to be able to focus on the analysis of this complex set of technology.

BOX 4

The data strategy at a glance

Publication data

- ▶ **Source:** Scopus database.
- ▶ **Time frame:** Publications from 2000-2021.
- ▶ **Filtering:** Journal articles and conference proceedings, in English.
- ▶ **Volume:** 1,045,623 publications of which around 40,000 of the most cited per year were extracted for in-depth analysis.
- ▶ **Identification:** Publications within Neuroscience Subject Area following the database's All Science Journal Classification⁸ (ASJC)⁸.
- ▶ **Additional metrics:** Citation density used as an indicator of high-impact science.

Patent data

- ▶ **Source:** European Patent Office's Worldwide Patent Statistical Database (PATSTAT).
- ▶ **Time frame:** Patents from 2000-2020.
- ▶ **Filtering:**
 - Only priority filings.
 - Patents assigned exclusively to the technology field "Pharmaceuticals" excluded, to avoid overshooting.
 - Only English abstracts.
 - Only IP5 patents (see 3.2 *Patent Data*)
- ▶ **Additional metrics:** Additional data sources were used for details on applicant and inventor location and patent quality.
 - **Target area:** Neurotechnology patents were identified using a data-driven approach (see section 4. *An innovative approach to delineate the boundaries of a complex technology*).

8 Subjects classified under the Neuroscience Subject Area include Neuroscience (all), Neuroscience (miscellaneous), Behavioral Neuroscience, Biological Psychiatry, Cellular and Molecular Neuroscience, Cognitive Neuroscience, Developmental Neuroscience, Endocrine and Autonomic Systems, Neurology, Sensory Systems.

3.1 Publication data

We use the Scopus database to gather information about neuroscience-related research. Rather than formulating an explicit, self-determined definition of neuroscience, we rely on the subject area classification assigned by Scopus, at the journal level. Although this inclusive approach may unintentionally incorporate some unrelated content (i.e. potential false positives, technically), any such material will be ex-post excluded by using topic modeling approaches which help identify and remove topics and themes that are not neurotechnology-related or not primarily as such.⁹ (Gerrish and Blei, 2010; Paul and Dredze, 2014)

More precisely, we query the Scopus database for all English-language journal articles and conference proceedings appeared over the period 2000-2021 in the Neuroscience subject area. This corresponds to identifying 1,045,623 publications within neuroscience related journals during the period considered. Among these publications, we extracted bibliographic data for the 2,000 most cited publications per year, assuming citations to be a signal of relevance and impact (see Squicciarini, Dernis and Criscuolo, 2013). This results in a final sample of 40,000 neurotechnology articles, evenly distributed across time. **Figure 17** and **Figure 18** in appendix illustrate the number of citations by neuroscience publication cohort and clearly shows that our choice is unlikely to lead to the loss of relevant information and bias, given the citation patterns observed. More precisely, the citations a publication has received 2 years after publication correlate strongly with the total observable citations a publication will receive over time. Consequently, we only include publications up to 2021, since for publications published afterwards the citation rank would not be a reliable indicator of the quality of the publications.

This sample is used to identify various research areas and relevant terminology to establish linkages to relevant neurotechnology patents. This process of science-technology linking is explained further in section 4.3, *Science-technology linkages*.

3.2 Patent data

Patents are among the most common data sources used to measure technological change, invention and innovation (Griliches, 1998; Hagedoorn and Cloudt, 2003). Since patents relate to commercially applicable technologies, these technologies are typically closer to the market and to real-world applications than the ones documented in research papers. Consequently, we mainly leverage patent data to investigate which type of neurotechnology-related innovations are developed worldwide, where, and by whom.

The patent data we use for our study was retrieved from the EPO's Worldwide Patent Statistical Database (PATSTAT, Autumn 2021 edition), which contains bibliographic patent data from more than 100 patent offices over a period of several decades. We include all patents containing an

⁹ Converging technologies often present aspects that belong to different types of underlying technologies (e.g. bio and nano). This may lead to overshooting in case one were to include all those thus identified.

English language abstract in the period from 2000 to 2020. Since the patenting process as well as data consolidation process by the database providers is lengthy, post-2020 data may not accurately reflect the complete worldwide patenting pattern accurately at the time we perform the analysis.

To avoid duplicates caused by filing the same patent at multiple patent offices, we follow De Rassenfosse *et al.* (2013) and only include priority filings, meaning the first filed application of a patent family. In order to focus on technologies and patents with potential global impact, we only include priority patents from (EPO's DOCDB)¹⁰ patent families of two or more patent applications, including at least one application at one of the five IP Offices (IP5).¹¹

IP5 patents represent a subset of overall patents filed worldwide, which have the characteristic of having been filed in at least one top intellectual property offices (IPO) worldwide (the so called IP5, namely the Chinese National Intellectual Property Administration, CNIPA (formerly SIPO); the European Patent Office, EPO; the Japan Patent Office, JPO; the Korean Intellectual Property Office, KIPO; and the United States Patent and Trademark Office, USPTO) as well as another country, which may or may not be an IP5. This signals their potential applicability worldwide, as their inventiveness and industrial viability have been validated by at least two leading IPOs. This gives these patents a sort of "quality" check, also since patenting inventions is costly and if applicants try to protect the same invention in several parts of the world, this normally mirrors that the applicant has expectations about their importance and expected value. If we were to conduct the same analysis using information about individually considered patent applied worldwide, i.e. without filtering for quality nor considering patent families, we would risk conducting a biased analysis based on duplicated data. Also, as patentability standards vary across countries and IPOs, and what matters for patentability is the existence (or not) of prior art in the IPO considered, we would risk mixing real innovations with patents related to catching up phenomena in countries that are not at the forefront of the technology considered.

¹⁰ DOCDB is the EPO's master documentation database with worldwide coverage. It contains bibliographic data, abstracts, citations and the DOCDB simple patent family, but no full text or images.

¹¹ The five IP offices (IP5) is a forum of the five largest intellectual property offices in the world that was set up to improve the efficiency of the examination process for patents worldwide. The IP5 Offices together handle about 80% of the world's patent applications, and 95% of all work carried out under the Patent Cooperation Treaty (PCT), see <http://www.fiveipoffices.org>. [Dernis *et al.*, 2015]

4.

An innovative approach to
delineate the boundaries
of a complex technology

Neurotechnology, as an inherently interdisciplinary field that is fast-evolving, presents challenges in identification and characterization of its developments and applications in a timely fashion and at scale. To this end, we devise a novel methodology leveraging artificial intelligence-related approaches and exploit large corpora of data.

The point of departure is neuroscience research articles, which we can identify unequivocally based on a tagging system operated by Scopus itself.¹²

To correlate the scientific content and topics thus identified with those in related (patented) technologies, we isolate technology-specific keywords representative of these topics. Each topic's top keywords are aggregated into queries, which are then employed to conduct a semantic search within a patent database. This process emulates the novelty screening procedure typically performed by a patent specialist in response to a specific scientific discovery. To ensure precision and relevance, the models we deploy are specifically tailored to the unique linguistic constructs found in research literature and patent documents.

By automating these processes, we can delineate a pool of technologies associated with the topics discerned in neuroscience research literature. Subsequent quantitative analysis of these patents enables us to identify pertinent technology classes and domains, comprehend ownership structures, and pinpoint core advancements.

The identification of neuroscience patents in this study presents a challenge due to the interdisciplinary nature of the field, which encompasses multiple technologies across various disciplines. To address this issue, we employ a multi-step approach that begins with the automated identification of latent themes or topics and keywords in research literature. We then use these keywords and key-phrases to construct search queries for semantic search within the patent database. This approach allows for a combination of broad scope and specific subfield targeting, such as "Sleep and Memory Consolidation", and can be complemented with domain expertise.

Following this methodology, we aim at providing a comprehensive mapping of the neurotechnology landscape as well as of the entities involved in developing these technologies. Substantially automatizing the identification of neurotechnology-related developments aims at making it possible to update this characterization as the technology evolves, thus helping to provide accurate and up-to-date evidence in support of policymaking. The approach proposed is flexible and can be applied to identify and characterize any other technological paradigm or trajectory¹³ (Dosi, 1982) that emerges over time.

The subsections that follow are quite technical, as they aim to give a precise account of the identification strategy devised. Readers uninterested in the proposed explanations may want to skip the rest of Section 4 and go directly to the results of the analysis, proposed in the next section.

12 In Scopus, serial titles are classified using the ASJC (All Science Journal Classification) Scheme and can be used to filter the search results. Neuroscience is listed as a Subject Area Classification in the Subject Area of Life Sciences. See more details at: https://service.elsevier.com/app/answers/detail/a_id/14882/supporthub/scopus/-/what-are-the-most-frequent-subject-area-categories-and-classifications-used-in/

13 Technological paradigm is defined as "a set of procedures, or a definition of the 'relevant' problems and of the specific knowledge related to their solution", while the technological trajectories is "the direction of advance within a technological paradigm". (Dosi, 1982)

4.1 Transformer-based topic modeling

We utilize a combination of text embeddings based on Bidirectional Encoder Representations from Transformer (BERT), dimensionality reduction, and hierarchical clustering inspired by the BERTopic methodology¹⁴ to identify latent themes within research literature. Latent themes or topics in the context of topic modeling represent clusters of words that frequently appear together within a collection of documents (Blei, 2012). These groupings are not explicitly labeled but are inferred through computational analysis examining patterns in word usage. These themes are 'hidden' within the text, only to be revealed through this analysis. They offer valuable insights into the main subjects or discussions within a large body of text, aiding in data organization and knowledge discovery. The BERTopic approach offers several advantages over traditional topic modeling techniques, such as Latent Semantic Analysis (LSA) or Latent Dirichlet Allocation (LDA), including reduced preprocessing, contextualized text representations, and the use of hierarchical clustering with *Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN)*¹⁵ for topic detection. Our method deviates from "standard" BERTopic use in two main ways: we utilize a specialized model for scientific language, and we employ Named Entity Recognition (NER) for identifying keywords and key-phrases.

SPECTER¹⁶ is used to embed extracted abstracts, as it is specifically designed for scientific text and has demonstrated superior performance in document-level tasks. Following this, we apply UMAP and HDBSCAN for clustering documents, resulting in a final collection of 218 topics (Cohan *et al.*, 2020).

4.2 Named entity extraction for science-keyword extraction

To generate insightful topic descriptors, we use keywords and key-phrases identified through NER with a specifically fine-tuned SciBERT transformer model that the authors OpenSourced (Jurowetzki and Bekamiri, 2022). This model identifies and extracts scientific keywords sorted into categories, such as task, method, and other scientific terminology. We argue that this method represents a significant improvement over simpler frequency-based keyword extraction methods. Keywords are then weighted by importance for each topic using cTF-IDF (Class-based Term Frequency – Inverse Document Frequency). c-TF-IDF, or Class-based Term Frequency-Inverse Document Frequency, is a text-mining method used to classify and differentiate documents based on the significance and frequency of the words they contain. It is an extension of the widely

14 BERTopic is a topic modeling technique that leverages transformers and Class-based Term Frequency – Inverse Document Frequency (c-TF-IDF) to create dense clusters allowing for easily interpretable topics whilst keeping important words in the topic descriptions (Grootendorst, 2022).

15 HDBSCAN is a clustering algorithm developed by Campello, Moulavi and Sander (2013) that finds clusters of varying densities in data. It does not require the user to specify the number of clusters in advance and is more robust to parameter selection than other clustering algorithms.

16 SPECTER is a pre-trained language model to generate document-level embedding of documents. It is pre-trained on a powerful signal of document-level relatedness: the citation graph (Cohan *et al.*, 2020).

used TF-IDF technique, which assigns weights to words based on their importance within a single document (TF-component) and their frequency across all documents (IDF-component). c-TF-IDF refines this process by calculating these values for entire categories of documents, not just individual ones (Grootendorst, 2022). This approach allows us to identify words that are particularly crucial to a specific category, providing a robust method to distinguish one class of documents from another within a large text corpus.

We further utilize OpenAI's GPT-4 model to enrich our understanding of topics' keywords and to generate topic labels (OpenAI, 2023), thus supplementing the expert review of the broad interdisciplinary corpus. Notably, we also employ GPT-4 to score the identified neuroscience and patent topics, assessing their relevance to neurotechnology. This step effectively removes topics that do not pertain to neurotechnology. The scoring process has been evaluated over several rounds, and the model has been prompted to be very permissive in the evaluation. Recently, GPT-4 has shown impressive results in medical contexts across various evaluations (Nori *et al.*, 2023), making it a useful tool to augment the information obtained from prior analysis stages, and to complement them. The automated process enhances the evaluation workflow, effectively emphasizing neuroscience themes pertinent to potential neurotechnology patents. Notwithstanding existing concerns about hallucinations (Lee, Bubeck and Petro, 2023) and errors in generative AI models, this methodology employs the GPT-4 model for summarization and interpretation tasks, which significantly mitigates the likelihood of hallucinations. Since the model is constrained to the context provided by the keyword collections, it limits the potential for fabricating information outside of the specified boundaries, thereby enhancing the accuracy and reliability of the output.

4.3 Science-technology linkages

Our approach aims to mimic what a domain expert performing a technology screening exercise would do in order to scope the patent space. For each identified topic, we use the top 100 keywords to generate queries, which are then utilized to perform "free-text-semantic-search" on the entire PATSTAT corpus. We employ the embedding and semantic search methodology proposed by Hain, Jurowetzki and Squicciarini (2022), using custom-trained SBERT for patents (Reimers and Gurevych, 2019) and TF-IDF models to create dense embeddings.¹⁷ Nearest neighbor approximation with the Annoy approach (Bernhardsson, 2018) help identify the closest matches between the content in scientific publications and that in patent documents. The search strings generated from scientific literature can thus be transformed into the same vector space as patent abstracts, allowing for efficient searches and identification of relevant patents.

Doing this we retrieve a large selection of patents related to neuroscience research literature, i.e. what we tag as our "neurotech" patents.

¹⁷ Embeddings, specifically Sentence-BERT (SBERT) type embeddings, are a method of converting sentences into numerical representations that a machine learning model can process. While the original BERT model developed by Google provided numerical representations for individual words, SBERT extends this to entire sentences. This means that each sentence is mapped to a specific point in a multi-dimensional space, with the distance between points reflecting the semantic similarity between the sentences. This sophisticated technique allows us to perform complex tasks that require understanding the meaning of whole sentences, like gauging sentence sentiment, conducting semantic searches, or classifying text documents.

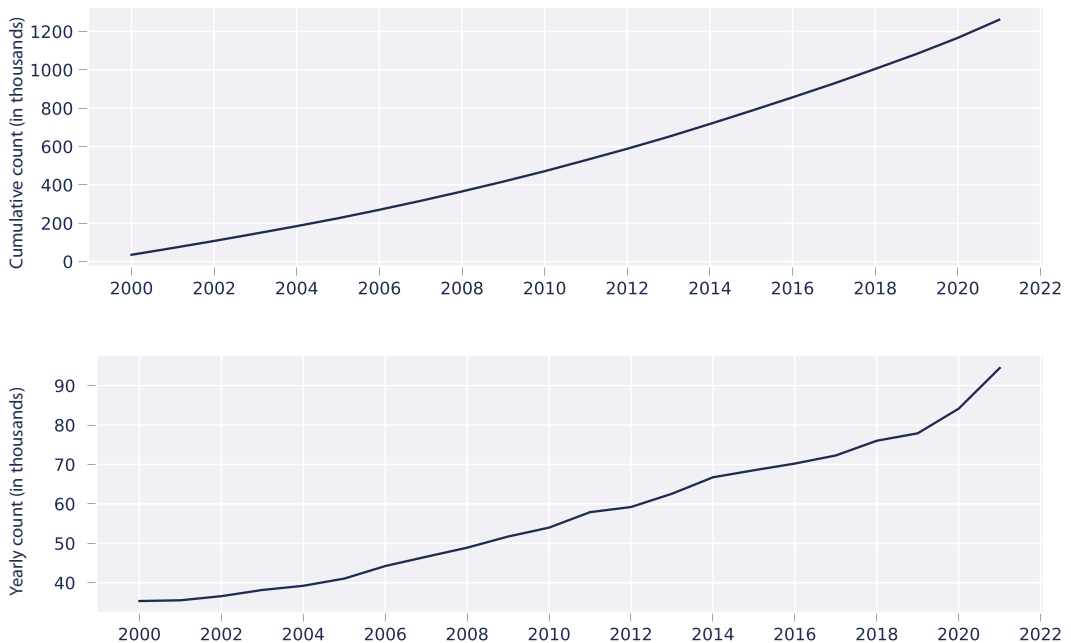
5.

Neurotechnology: key stylized facts

5.1 Neuroscience publications over time

Publications within a well-defined field of research, such as neuroscience, provide us with insights about what the field focuses on and how it has evolved over the last couple of decades. While neuroscience articles may contain research that directly relates and can be translated into technological developments, not all of them will do so and, in addition, not all technological developments can be protected through intellectual property rights,¹⁸ or may have reached the required applicability stage during the period considered.

Figure 2. Overall (top) and by year (bottom) number of neuroscience publications over time



Source: authors' own compilation on data from Scopus (2000-2021)

Figure 2 shows the evolution of overall and annual publications in neuroscience. The overall number of publications in neurosciences has seen a remarkable increase – nearly 35 folds between 2000-2021, going from 35,000 to about 1.2 million in 2021. The annual number of publications in neuroscience has more than doubled since 2000, with over 90,000 publications recorded in 2021 alone. This mirrors the constant growth of the field over the last two decades, with an increase in the pace of growth since 2019.

¹⁸

To qualify for patent protection, an invention must satisfy three primary conditions, as for instance detailed in the Manual of Patent Examining Procedure (MPEP) Section 2100. First, it must exhibit novelty, indicating it is not previously known or used in the field. Second, the invention must surpass the threshold of non-obviousness, meaning it is not an evident modification or extension of existing work to those skilled in the field. Lastly, the invention must meet the criterion of usefulness, ensuring it possesses a specific, tangible utility (United States Patent and Trademark Office, 2023).

To identify and analyze the most important scientific developments occurred over the period considered, we focus on the 2,000 most cited publications per year. Citations are well known indicators of scientific impact and relevance (Aksnes, Langfeldt and Wouters, 2019), as they mirror the fact that subsequent scientific contributions have built upon the cited article. We consider the top cited 2,000 articles per year, to avoid possible biases related to older articles being likely to receive a comparative greater number of citations than more recent ones, only on the basis of pure mechanics, i.e. more years during which they may be cited. The older a publication, the greater the time span during which an article can be cited and, hence, the more likely to have a greater number of citations than more recent articles.

Table 1 provides an overview over the most popular publication outlets (journals or conferences) where top cited articles appeared, as well as of the keywords provided by the authors. When publishing scientific articles, authors are asked to provide a limited number of keywords (normally between three and five) that best explain or relate to their contribution. This helps indexing and searching, and helps understanding the main topics of the contributions considered. Also, in Table 1, more used keywords are also likely to relate to longstanding or more consolidated neurotechnology fields of research, i.e. developments that have been occurring for a relatively longer time frame. As we here exploit information related to the top 2,000 cited papers over the period considered, keywords related to topics that have been the object of research for many years are likely to emerge among the top ranked ones.

As expected, the most popular outlets are relatively more generic ones, covering the overall field, such as the *Journal of Neuroscience*, *Neuron*, and *Nature Neuroscience*. However, among the top ranked journals, interdisciplinary outlets such as *Elife*, *Plos Biology*, *Trends in cognitive sciences*, and *Neurocomputing* also appear.

5.1.1 Neuroscience key topics and leading contributors

When it comes to the keywords, those being used more often relate to conditions and diseases associated with the brain in general, such as *Alzheimer's disease*, *Parkinson's disease*, *Neurodegeneration*, and *Neuroinflammation*. Other often used keywords conversely specify regions or components of the brain, such as the *Hippocampus*¹⁹ or *Microglia*,²⁰ or techniques such as the functional Magnetic Resonance Imaging (*fMRI*). Notably, Covid19 appears among the top used keywords, despite its appearance in 2019 only, thus signaling that the focus of most of the neuroscience research carried out from 2019-2021 centered around shedding light on the effects of the pandemic over the brain.

-
- 19 Hippocampus is a complex brain structure embedded deep into temporal lobe. It has a major role in learning and memory, while it can get damaged by a variety of stimuli due to its plastic and vulnerable structure. (Anand and Dhikav, 2012)
 - 20 Microglia are the major myeloid cells of the central nervous system (CNS). They are implicated in physiologic processes and in the pathogenesis of several CNS disorders (Ransohoff and El Khoury, 2016).

Table 1. Most popular neuroscience journals and keywords

Journal	n	Keywords	n
Journal of Neuroscience	1866	Alzheimer's Disease	1199
Neuron	1674	Depression	859
Nature Neuroscience	1108	Parkinson's Disease	776
NeuroImage	981	Hippocampus	730
Brain Research	897	Schizophrenia	700
EMBO Journal	847	Inflammation	686
eLife	701	fMRI	666
Biological Psychiatry	668	Microglia	590
Neuroscience Letters	661	Neurodegeneration	498
Molecular Psychiatry	592	Stress	495
Nature Reviews Neuroscience	553	Cognition	494
Neuroscience	493	Anxiety	468
Annals of Neurology	483	Aging	467
Neuroscience and Biobehavioral Reviews	474	Dopamine	454
Neurocomputing	456	COVID-19	439
Movement Disorders	424	Stroke	423
PLOS Biology	422	Neuroinflammation	422
Trends in Cognitive Sciences	416	Epilepsy	418
European Journal of Neuroscience	398	Multiple Sclerosis	415
Investigative Ophthalmology and Visual Science	363	Meta-analysis	407

Note: Each column of the table represents a distinct category of information. The left-hand side column displays the most popular outlets, while the right-hand side column showcases the most popular topics. The keywords presented in the right-side column are not categorized by outlet but rather by their independent nature.

Source: authors' own compilation on data from Scopus (2000-2021)

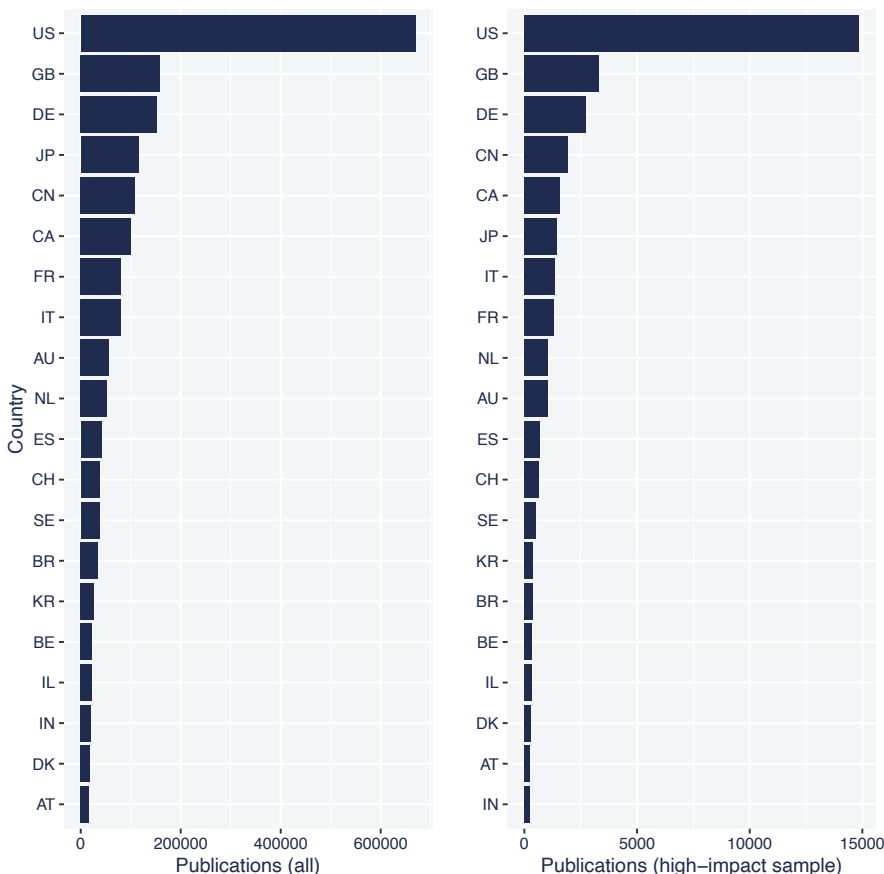
Figure 3 reports the top-20 countries in terms of neuroscience-related publications appearing overall (left) as well as in our high-impact subsample (right). Within the high-impact sample that we used in the subsequent analysis, the United States emerges as the leading country, accounting for 40% of them – which is over four times as much as the highly cited publications owned by the second ranked, i.e. the United Kingdom (9%). Germany (7%), China (5%), Canada (4%), Japan (4%), Italy (4%), France (4%), the Netherlands (3%), and Australia (3%) follow. Overall publications

number-related rankings and rankings based on top cited publications differ, although not in an important way, suggesting that quantity and quality go hand in hand. The top-10 countries in the list account for over 80% of high-impact publications, whereas 70% of countries in the world have less than 10 high-impact neuroscience publications over the period considered.

Among the emerging economies (i.e. the BRICS – Brazil, Russia, India, China, and South Africa), China, Brazil and India rank within the top 20. When it comes to Latin America, Brazil is the leading contributor to high-impact neuroscience publications in the region, ranking 15th globally with 373 publications. Other significant contributors are Mexico and Argentina, ranked 32nd and 33rd respectively.

Countries in Africa and in the Arab States, with the exception of South Africa, are largely absent from the top-level positions of the ranking. Jordan leads with 27 publications, followed by Saudi Arabia with 20. Overall, figures point to important difference and possible need for increased investment and development in neuroscience research in the regions that are currently lagging behind.

Figure 3. Neuroscience publications by country



Source: authors' own compilation on data from Scopus (2000-2021)

5.1.2 Shedding light on Neuroscience's main applications

Following our NLP and deep learning-based methodology, we use the text found in the publication title and abstract to identify technology related topics and associated applications. Doing so, we identify 218 latent topics defined by key scientific terms, which nevertheless differ in size, i.e. in terms of the number of the associated documents, and that fluctuate in terms of relevance over time. Following this methodology each publication can be only associated with one topic.

As indicated when overviewing the approach implemented, we use OpenAI's GPT-4 model via its API to interpret the keyword representations of these identified topics, and then get our findings validated by neuroscience experts. In Box 5, the research corpus is categorized into broad areas and each is accompanied by the three most representative topics that fall within them. These topics span areas such as neurological disorders, neuroimaging, vision studies, artificial intelligence applications in neuroscience, molecular biology, cognitive and neurobehavioral studies, general health-related neurological aspects, and genomics. They offer a comprehensive look into the breadth of research being conducted in contemporary neuroscience, illustrating the multi-disciplinary and inter-related nature of this research field. The complete list of identified topics can be found in **Table 7** in Appendix.

Out of the 218 topics, GPT-4 helped us identify 109 that are potentially associated with neurotechnology-related applications. These 109 topics, and the patents identified as being related to them, formed the focus of our subsequent analysis.

BOX 5

Main categories of identified neuroscience topics and categorized example topics

- ▶ Neurological Disorders and Diseases
 - Fragile X Syndrome
 - Epilepsy Surgery Neuroimaging
 - Huntington's Disease
- ▶ Neuroimaging and Neurotechnology
 - Bilingualism Neuroimaging
 - Deep Learning Neuroimaging
 - TBI Neurotechnology
- ▶ Ophthalmology and Vision
 - Ophthalmology, Corneal Treatments
 - Retinal Photoreceptors
 - Ocular Refractive Errors
- ▶ Artificial Intelligence and Machine Learning
 - ANN Optimization
 - ML Classification
 - Deep Learning Vision
- ▶ Molecular and Cellular Biology
 - DNA Repair
 - Cellular Senescence
 - Cell Death Mechanisms
- ▶ Cognition and Neurobehavioral Studies
 - Numerical Cognition
 - Emotion Analysis
 - Spatial Memory
- ▶ Neurological Aspects of General Health
 - Inflammation, Cardiovascular, Joints
 - Exercise Cognition
 - Diet, Exercise, Cognition
- ▶ Genetics and Genomics
 - Brain Tumor Genomics
 - Evolutionary Genetics
 - Genetics, Neuroimaging, Psychiatry

To demonstrate the application of GPT-4 in our setting, readers may consider the following example of the interpretation of one topic in **Box 6**.

BOX 6

AI-assisted topic interpretation

A keyword-based topic representation (using top 100 keywords) would typically look like this:

DBS, STN, subthalamic nucleus, Parkinson's disease, PD, Deep brain stimulation (DBS), deep brain stimulation (DBS), basal ganglia, GPi, STN-DBS, deep brain stimulation, subthalamic nucleus (STN), movement disorders, tremor, STN DBS

Using automated interpretation of these keywords with GPT-4 we obtain:

Summary: Deep brain stimulation (DBS) of the subthalamic nucleus (STN) for treating Parkinson's disease and other movement disorders.

Application: DBS is used to alleviate motor symptoms in Parkinson's disease, essential tremor, dystonia, and OCD by targeting the basal ganglia and modulating oscillatory activity.

In addition, the model classifies this topic 5 on a 1-5 regarding its relevance/affiliation with patentable neurotechnology.

Titles of research articles that the approach sorts into this topic include:

- ▶ Optimizing Deep Brain Stimulation Parameters in Obsessive-Compulsive Disorder
- ▶ Utility of Deep Brain Stimulation Telemedicine for Patients With Movement Disorders During the COVID-19 Outbreak in China
- ▶ A prospective international multi-center study on safety and efficacy of deep brain stimulation for resistant obsessive-compulsive disorder

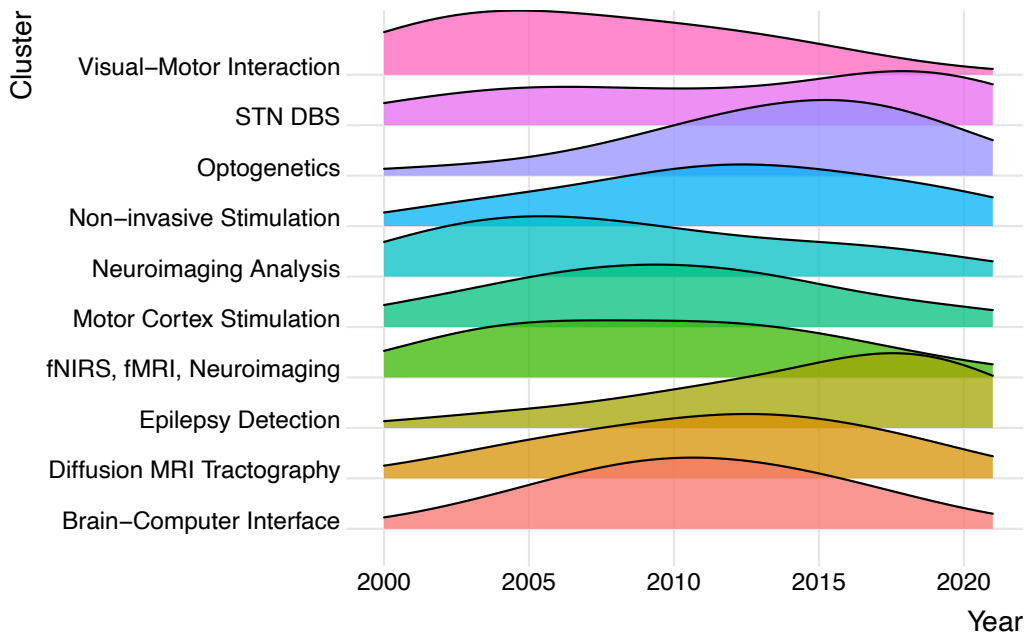
Other topics, typically associated with neurotechnology that we identify in the scientific publication corpus are:

- ▶ Automatic seizure detection and diagnosis of epilepsy using EEG signals and machine learning methods.
- ▶ Optogenetics: A neuroscience technique that uses light to control and monitor neural activity with high precision.
- ▶ Brain-computer interfaces (BCIs) that enable communication and control through brain signals, often using electroencephalography (EEG) for signal processing.

- ▶ Functional near-infrared spectroscopy (fNIRS) and functional magnetic resonance imaging (fMRI): Neuroimaging techniques used to study brain activity, particularly in relation to language processing, motor tasks, and hemodynamic responses.
- ▶ Investigation of brain activity and neural dynamics using EEG, MEG, and fMRI techniques.
- ▶ Non-invasive brain stimulation techniques such as transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) for motor function recovery in stroke patients, to modulate motor cortex excitability and motor function.
- ▶ Diffusion MRI tractography, a neuroimaging technique that maps white matter tracts and brain connectivity using diffusion tensor imaging (DTI) and advanced algorithms.
- ▶ Investigation of the interaction between visual perception, attention, and motor learning using neuroimaging and stimulation techniques.

Neurotechnologies also appear in topics that are mainly related to specific neurological disorders and diseases, for instance the investigation of sleep disorders and their impact on health using neurotechnology.

Figure 4. Development of publications in top technology topics



Note: Specific neurotechnology-related topics are visualized by the publication density over time (smoothened).

Source: authors' own compilation on data from Scopus (2000-2021)

Figure 4 showcases the evolution of neuroscience research from 2000 to 2021, highlighting specific neurotechnology-related visualized by the publication density over time (smoothened).

Brain-Computer Interface (BCI) research proliferated around 2010 and has since maintained a steady presence, reflecting its significant role in areas such as rehabilitation and human-computer interaction. Similarly, Diffusion MRI Tractography has also seen notable growth, peaking around 2011-2013, reflecting its importance in understanding neurological disorders and brain function.

Interest in Epilepsy Detection spiked in 2017 and 2018, mirroring the wider adoption of AI and machine learning methods in healthcare. During this period, there was also a surge in interest in Motor Cortex Stimulation, indicating its potential for stroke rehabilitation and motor recovery.

Neuroimaging Analysis has consistently attracted interest in neuroscience, peaking around 2004, demonstrating its value in studying brain activity and language comprehension. Over the years, Non-Invasive Stimulation and Optogenetics have also grown in popularity, peaking in 2013 and 2008, respectively. The former has been especially valuable in rehabilitation settings, while the latter enables in-depth study of neural functions.

Despite experiencing top levels in 2016 and 2017, Deep Brain Stimulation (DBS) has consistently been a subject of research due to its potential in treating conditions such as Parkinson's disease and essential tremor.

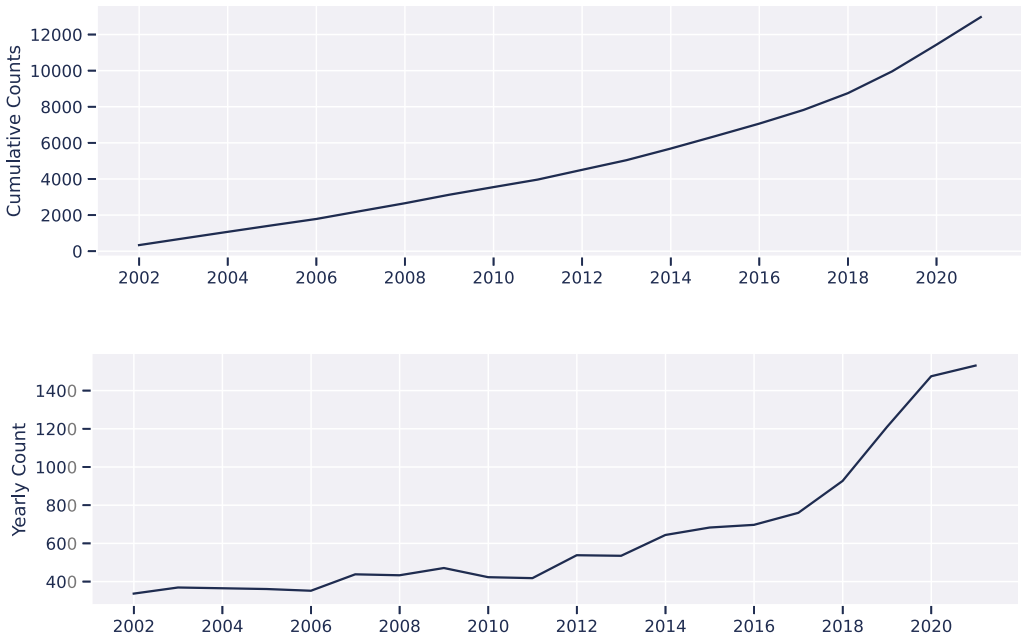
Visual-Motor Interaction and neuroimaging with fNIRS and fMRI saw their research be at the highest in 2018 and 2005, respectively, highlighting their importance in enhancing motor learning and skill acquisition.

It is important to consider that these trends are based on a dataset restricted to the 2000 most cited publications per year, meaning the specific representation of certain topics might not linearly mirror their overall development. Despite this limitation, these trends offer an insightful overview of the ever-evolving landscape of neuroscience research.

5.2 Neurotechnology patents

In the following, we provide an overview of key results from the patent-based analysis. By means of semantic search, we query the EPO's PATSTAT patent database in search of patent documents related to the topics identified in the analysis based on scientific publications. We do so as scientific publications are likely the basis for the development of relevant commercial technologies and the language contained therein allows to identify patents having similar or related content.

The progression of overall and yearly IP5 patent applications in neurotechnology is shown in **Figure 5** below. Between 2000 and 2020, the total number of patent applications in this field increased significantly, experiencing a 20-fold increase from less than 500 to over 12,000. In terms of annual figures, a consistent upward trend in neurotechnology-related patent applications emerges, with a notable doubling observed between 2015 and 2020.

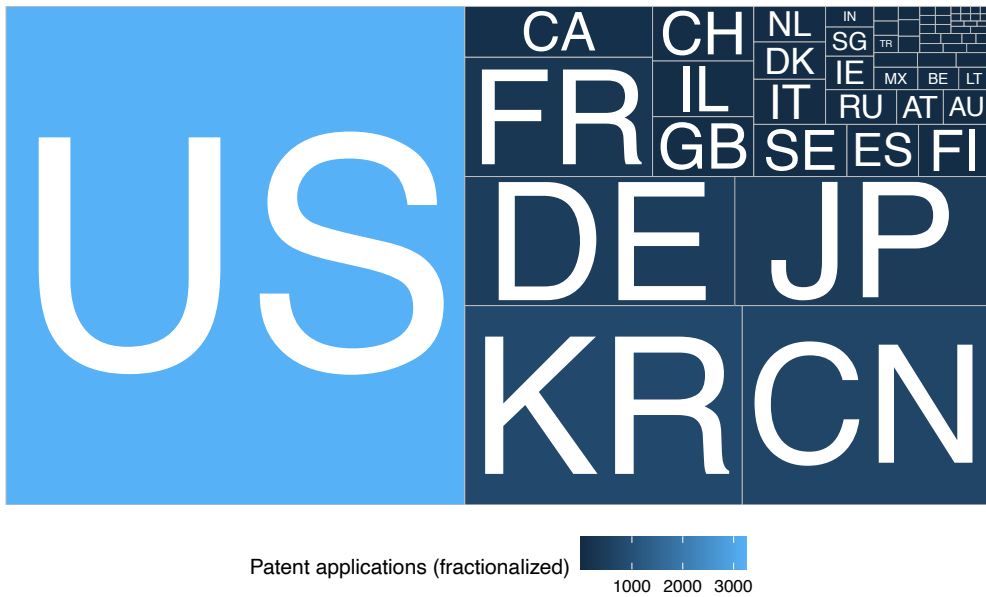
Figure 5. Overall (top) and by year (bottom) IP5 Neurotechnology-related patents over time

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

5.2.1 Top neurotechnology innovators around the world

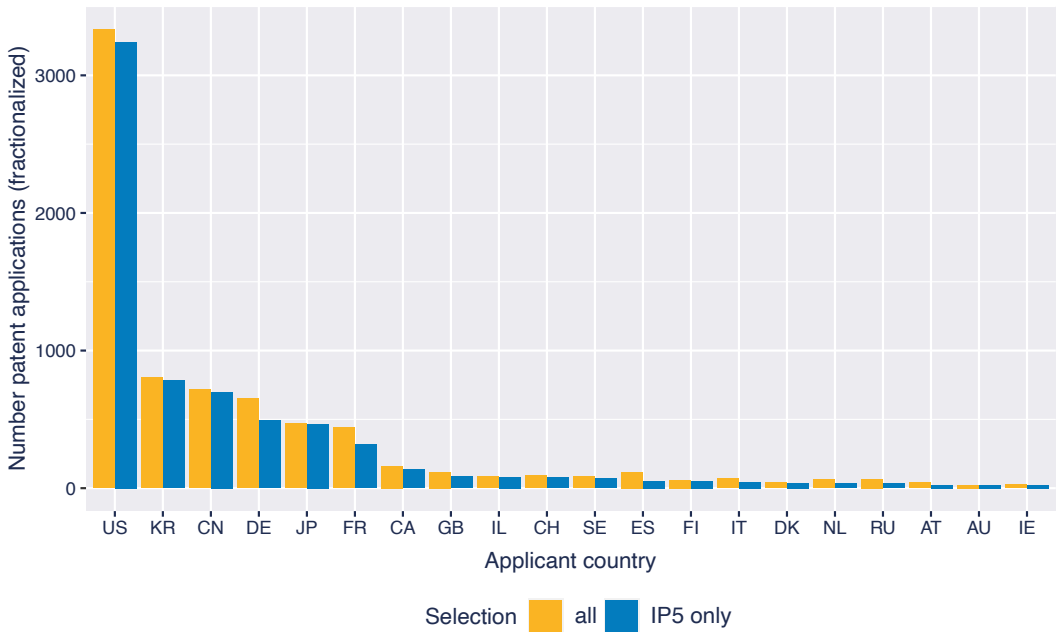
Figure 6 shows the top countries in terms of number of neurotechnology patents owned, as measured by fractional counts based on the location of patent applicants.²¹ The figure clearly indicates the United States to be the main place where neurotechnology-related innovations are generated. It accounts for 47% of all worldwide IP5 patent applications in neurotechnology. The second most important innovator in terms of neurotechnology patents is Korea (11%), followed by China (10%), Japan (7%), Germany (7%) and France (5%). These six countries together account for 87% of IP5 neurotech patents applied over the period considered.

21 Fractional counts are the standard approach used in order to avoid duplications. See Squicciarini, Dernis and Criscuolo (2013) for more details.

Figure 6. Patent applicants in neurotechnology by country

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

As mentioned, our analysis is mainly based on IP5 patent families, i.e. patents filed at least in two patent offices, one of them being one of the five largest patent offices worldwide, i.e. USTPO, EPO, JPO, KIPO, SIPO. We do so in order to focus on technologies with potential global impact. While this approach represents a good practice in international patent statistics, it might leave partially or fully undetected potential domestic developments. To shed light on the possible differences that exist in terms of country-specific innovations, as compared to innovations having the potential to impact the rest of the world, **Figure 7** depicts the number of neurotechnology patent applications of top countries in terms of patents filed in the very same country, as well as IP5 applications. While for most countries these numbers are very similar, a number of European countries, including France, Germany, and Spain, exhibit a visibly higher number of non-IP5 applications.

Figure 7. Country of neurotechnology patent applicants, all vs. IP5

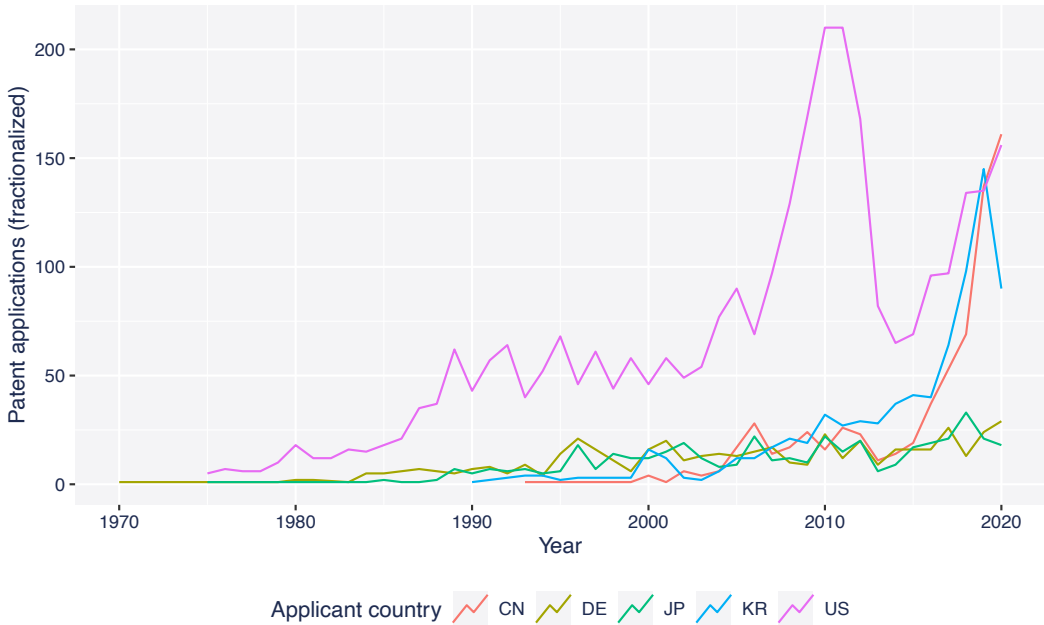
Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Figure 8 depicts the development of annual patent applications in the top-neurotechnology developing countries over time. As already indicated in Figure 6 and Figure 7, the development of neurotechnology is led by the United States. An initial peak of neurotechnology patent applications emerges in 2010, followed by a sharp decrease in terms of number of patents filed per year until 2014, and another wave of sustained development up to 2020. In contrast, South Korea appears as a latecomer, exhibiting its first IP5 neurotechnology application after 1990. Since then though, it shows a steady increase in applications, overtaking Germany in the late 2000s, and becoming the second largest developer of neurotechnology worldwide. In the late 2010s, South Korea accounts for a number of neurotechnology patent applications per year which is roughly similar to the one of the United States. This is in line with the findings in *World corporate top R&D investors: Shaping the future of technologies and of AI* (Dernis *et al.*, 2019), which show Korean companies to account for an important share of artificial intelligence technologies, and the fact that a number of neurotech developments rely on artificial intelligence and build on neural networks.

Also impressive is the pace of Chinese Neurotechnology IP5 patent applications, which increase sharply in the mid-2010s, leading to China accounting for roughly the same amount of patent applications as the United States at the end of the period considered.²²

22

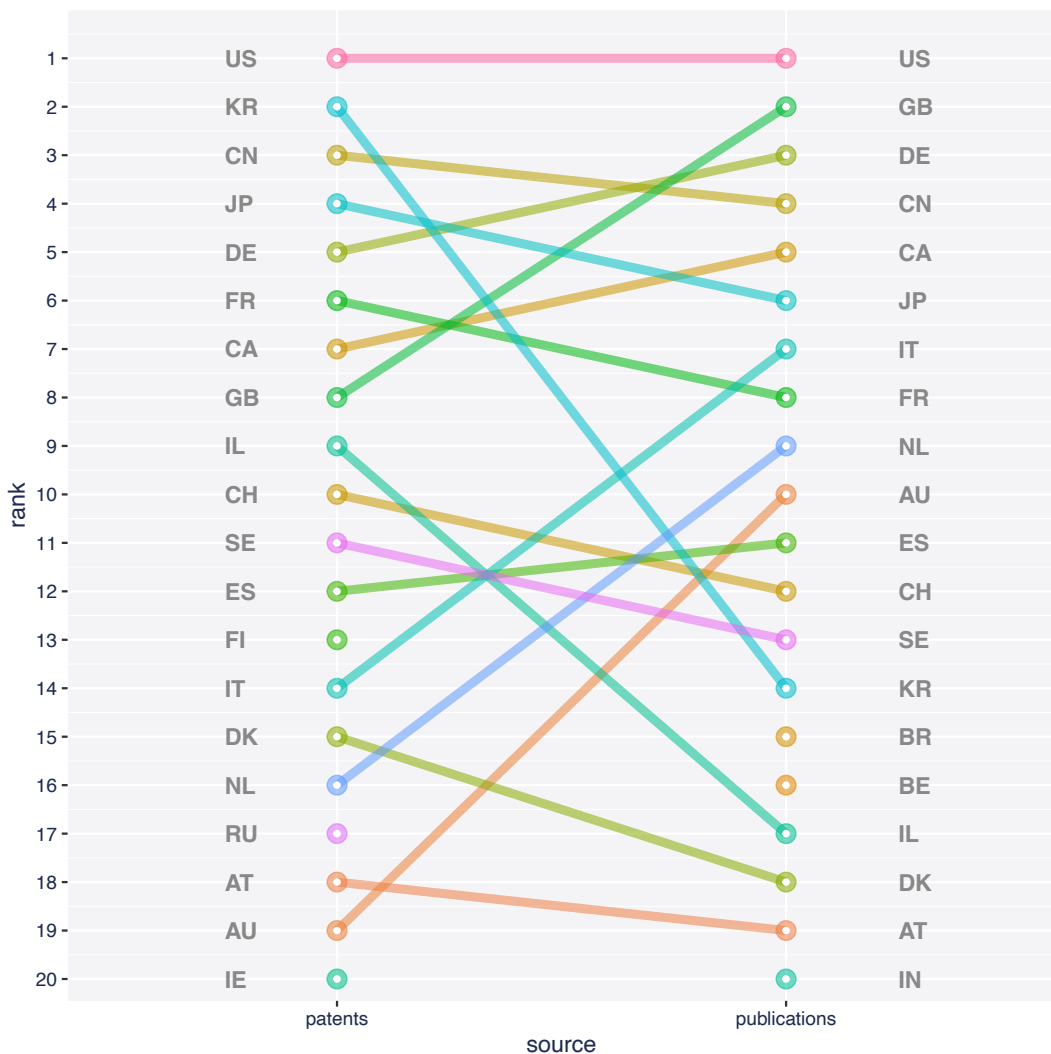
It should be noted that statistics related to the last year of observations may be represent an underestimation, as truncation prevents from fully seeing the number of patents applied until not less than 30 months after filing.

Figure 8. Number of neurotechnology patents over time in top-5 countries

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Comparing how countries rank in terms of production of scientific publications and patents related to neurotechnology provides important information about their ability to translate scientific advancements into industrially viable applications. A number of factors contribute to enable or hinder the transformation of new knowledge into innovations, including relevant human capital, industry structure, existing normative framework, and the existence and functioning of financial markets supporting innovative developments. As can be seen from **Figure 9** below, the United States rank on the top in relation to both abilities, whereas China, France and Korea especially are seemingly very good at leveraging the knowledge they create (and even the knowledge created elsewhere) and translate that into patented inventions. On the other side of the spectrum, a number of European countries, including the United Kingdom, Germany and Italy, as well as countries such as Canada, Brazil and Australia, are seemingly lagging behind in their ability to transform the neurotech knowledge they generate into patentable innovations.

Figure 9. Country ranking neuro patents vs. publications



Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020) and from Scopus (2000-2021)

5.2.2 Patent quality

Not all that glitters is gold, and the technological as well as the economic significance of patents varies broadly (Basberg, 1987). While all patents must meet objective criteria in terms of novelty and utility in order to be granted, the innovation they aim to protect may still represent an incremental or limited improvement to an existing technology. Also patents' economic value is contingent on firm, technology, market, and timing related factors, among others.

To shed light on what is generally called the quality of patents (Squicciarini, Dernis and Criscuolo, 2013), **Table 2** below shows that, based on patent citations, the most valuable patents are those related to inventions made in Germany, followed by the United States and China. When it comes to market coverage of the protection, as proxied by the family size of the patent (i.e. the number of countries in which the very same innovation is protected, we see clearly that the United States come on the top, followed by Japan, and by Germany and China, ex aequo. In both cases, Korean patents emerge as the one that are relatively less cited and are covered in a relatively smaller number of countries compared to their competitors.

Table 2. Patent quality per country

Country	Forward Citations (cohort rank)	DOCDB family size (cohort rank)
DE	0.80	0.66
US	0.72	0.77
CN	0.68	0.66
JP	0.67	0.68
KR	0.66	0.54

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

5.2.3 Who owns neurotech patents?

Patent applicants are the legal entities owning the intellectual property rights associated with a patent. In the following **Table 3** we list the five top neurotechnology applicants per country in relation to the top five countries in terms of number of neurotechnology IP5 patent applications.

This allows us to see that, while in most countries applicants are private sector organizations, in the case of China and of South Korea in particular, top neurotech applicants are (public sector) universities or other institutions, not companies.

Table 3. Top five neurotech patent applicants per top country²³

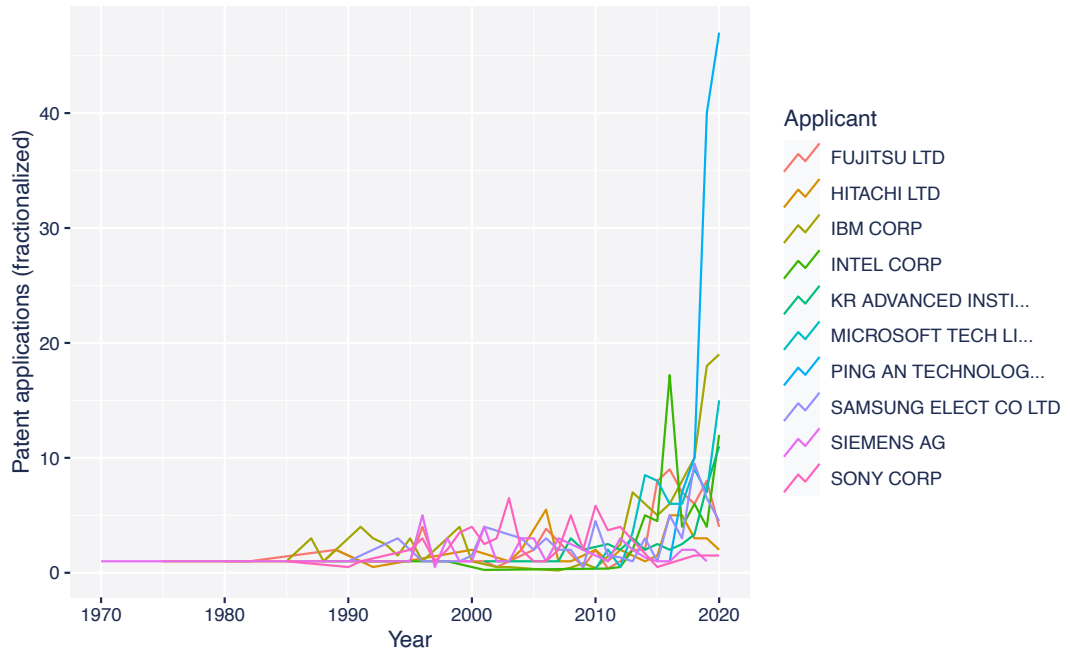
Country	Applicant name	n
US	IBM Corporation	126
US	Microsoft Technology Licensing, LLC	76
US	Intel Corporation	64
US	General Electric Company	52
US	Microsoft Corporation	51
KR	Samsung Electronics Co., Ltd.	72
KR	Korea Advanced Institute of Science & Technology	52
KR	Electronics and Telecommunications Research Institute	46
KR	LG Electronics, Inc.	26
KR	Korea University Research and Business Foundation	25
CN	Ping An Technology (Shenzhen) Co., Ltd.	105
CN	Huawei Technologies Co., Ltd.	37
CN	Zhejiang University	30
CN	Tencent Technology (Shenzhen) Co., Ltd.	25
CN	Shenzhen Institutes of Advanced Technology	23
JP	Fujitsu Ltd.	78
JP	Sony Corporation	69
JP	Hitachi, Ltd.	54
JP	Canon Inc.	39
JP	NEC Corporation	25
DE	Siemens AG	52
DE	Siemens Healthcare GmbH	32
DE	Robert Bosch GmbH	21
DE	Philips Patentverwaltung GmbH	12
DE	BASF AG	9

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

²³ We keep Microsoft Technology Licensing LLC and Microsoft Corporation separately as they are different entities. Aggregating figures at the conglomerate level would put Microsoft at the top of the ranking.

It is also very interesting to see the evolution of applications over time by different entities. **Figure 10** below illustrates the number of annual patent applications of the ten applicants with the overall highest number of patent applications. This allows the impressive increase in applications by the Chinese Ping An Technologies emerging in 2020. IBM follows in terms of number of applications in 2020, although exhibiting less than half of the applications belonging to the top applicant.

Figure 10. Neurotechnology patents of top applicants over time



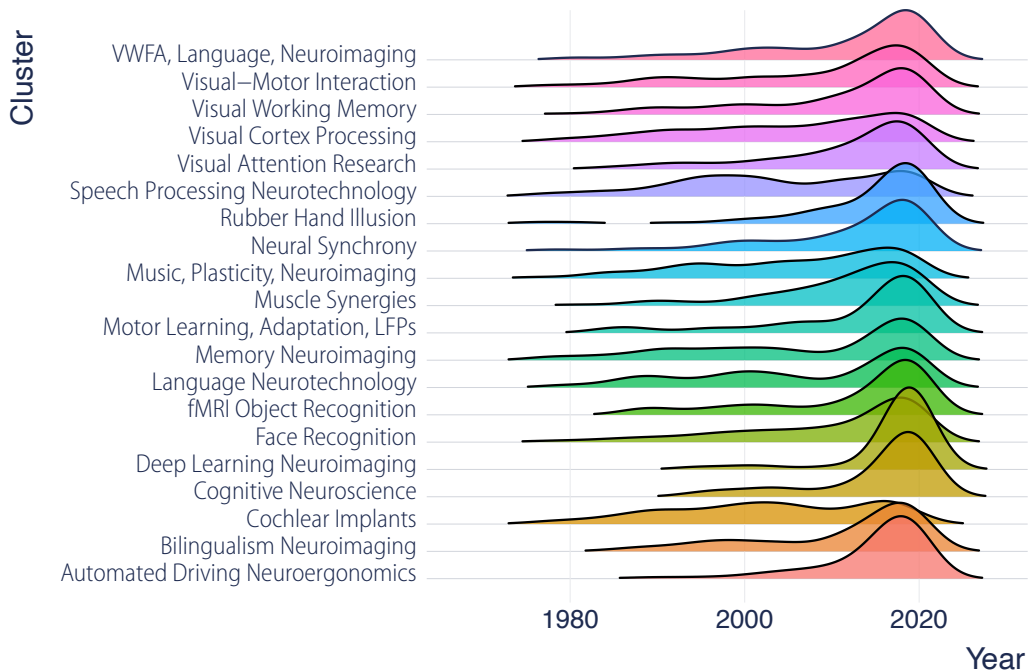
Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

5.2.4 Technologies associated with neuroscience research topics

Figure 11 illustrates the trend in patent applications per year related to the key technology topics identified earlier in neuroscience publications. Focusing on the 20 topics with the overall highest number of patents, we see that most of them experienced a sharp increase in patenting activity in the 2010s, with only a few, such as *visual attention processing*, *speech processing*, and *cochlear implants*, displaying notable earlier activity, i.e. since the late 1980s. It is also interesting to note the impressive increase exhibited in recent years by *deep learning neuroimaging*, *cognitive neuroscience* and *rubber hand illusion* (Bartoletti *et al.*, 2023), as discussed further in section 5.3 *A closer look at neurotechnology patents* below. Deep learning neuroimaging is the ability to learn highly complex and non-linear patterns from neuroimaging data (see e.g. Avberšek and Repovš, 2022, for a survey). Cognitive neuroscience aims to understand how the brain functions

and achieves performance, by studying the biological processes that underlie human cognition, especially through the relation between brain structures, activity, and cognitive functions (see e.g. Churchland and Sejnowski, 1988, as an early overview of this long-standing field of research). The rubber hand illusion is a scientific approach used in neuroscience to reveal how the brain understands the body, by exploring how the mind combines information from the senses to create a feeling of body ownership (see e.g. Bartoletti *et al.*, 2023 and Finotti *et al.*, 2023).

Figure 11. Patent applications in top technology fields (identified based on scientific publications)



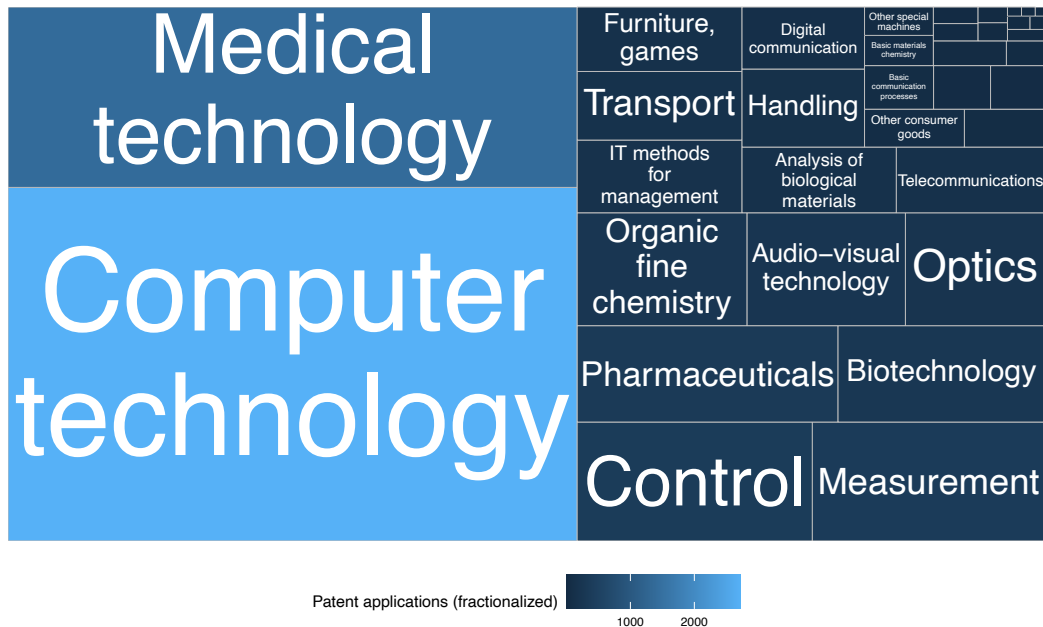
Note: The y axis represents the top 20 key technology topics identified earlier in neuroscience publication. Information provided for years beyond 2020 is partial due to truncation and the inherent delay in the public release of patent documents. Patent documents typically become publicly available no sooner than 18 months after their filing date, and their publication may be further delayed, especially if they follow an international filing route, such as the Patent Cooperation Treaty (PCT).

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

In terms of technology fields associated to neurotechnology patents, a breakdown can be seen in **Figure 12**. Technology fields are identified based on the technology class in which patents have been registered, using fractional counts, and aggregating patent fields according to the WIPO taxonomy (Schmoch, 2008). Interestingly, Computer Technology appears to be the most significant technology field in which neurotechnology patents are filed, followed by fields such as Medical Technology, Biotechnology, and Pharmaceuticals, which are the ones that we would

expect. This hints at the growing importance of algorithmic applications in neurotechnology in general, including neural computing techniques, which are rapidly increasing in popularity, use and impact.

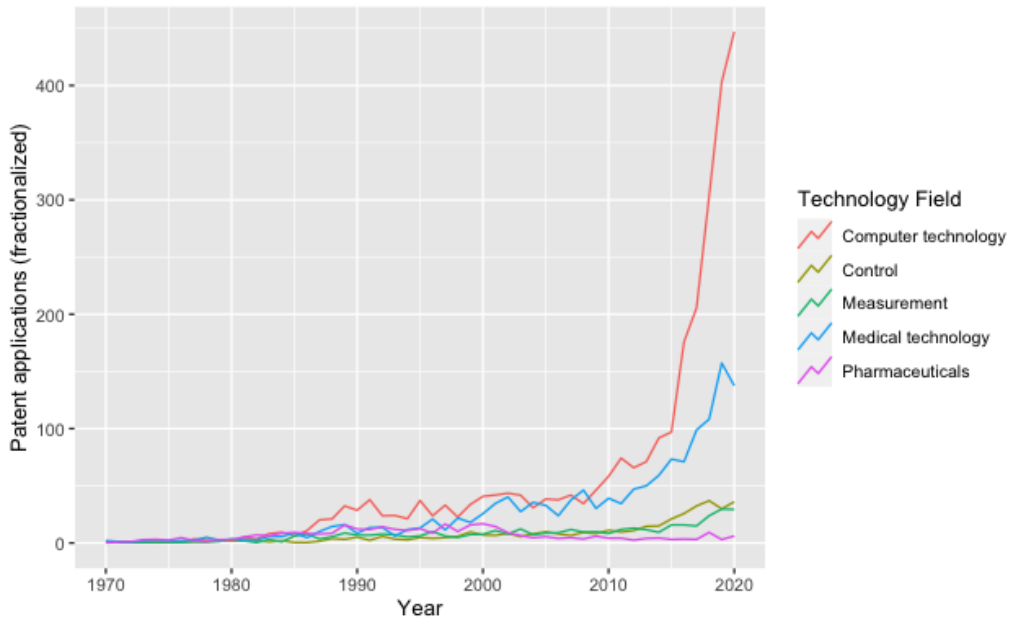
Figure 12. Number of neurotechnology patents by technology field



Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Figure 13 depicts the development of neurotechnology patents applications over time by technology field. A clear shift of technological paradigm around 2000 can be seen, whereby computer and medical technologies used in neurotechnology experience a sharp increase in patent applications as compared to traditionally important technology fields such as biotechnology and pharmaceuticals. In detail, the number of annual patent applications in 2020 as compared to 2015 represents an increase by 355% in computer technologies and 92% in medical technology.

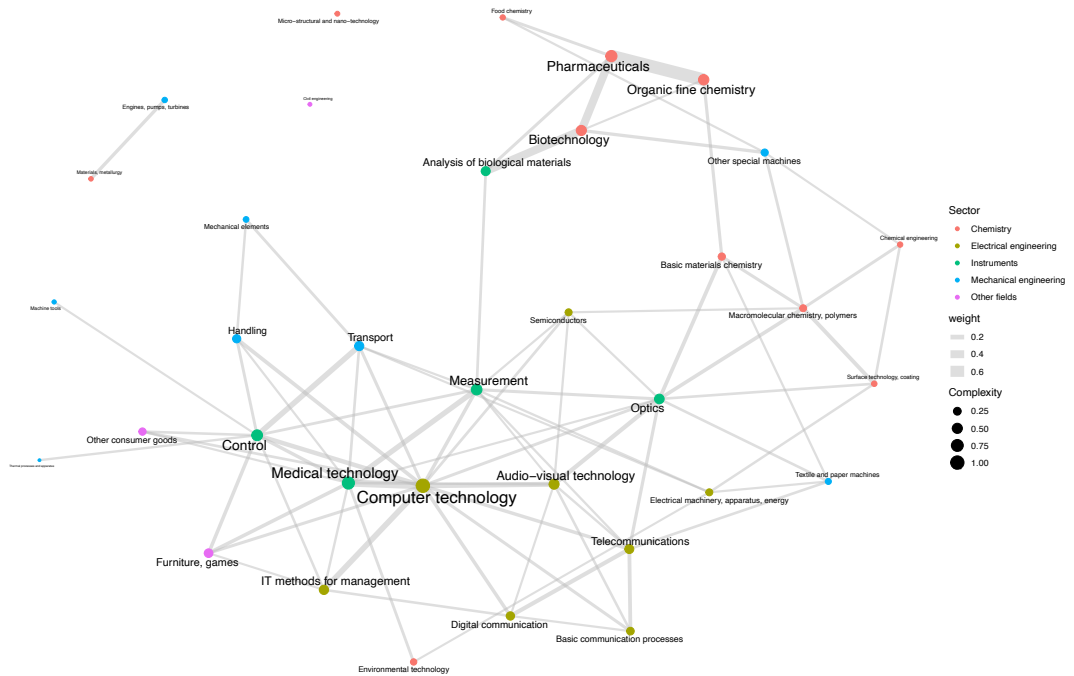
Around 2015 the sharp increase in computer technology-related neurotechnology that we observe mirrors the rapid pace of digitalization occurring in the field. In recent years, neurotechnology and artificial intelligence appear to have been growing hand in hand, a fact that triggers important ethical concerns in relation to ensuring that the development, use and deployment of these technologies do not impinge on human rights, fundamental freedoms and human dignity.

Figure 13. Number of neurotechnology patents over time in top five technology fields

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Most patents are assigned to multiple technology fields simultaneously. Analyzing the resulting pattern of co-occurrence can offer important insights about the relationship between technology fields in neurotechnology. **Figure 14** displays such relationship, i.e. how technology fields in neurotechnology relate to each other in a technology space network. The nodes represent technology fields whereas the edges show their relatedness (Balland *et al.*, 2022) in terms of normalized co-occurrence on patents, fact that mirrors the “strength” of the relationship. We see three main clusters emerge around (i) chemistry (mainly biotechnology and pharmaceuticals), (ii) digital technologies (mainly computer science), and (iii) the instruments sector (optics, measurement, analysis of biological material, etc.).

While chemistry and digital technologies appear internally densely related, i.e. corresponds to a relatively more homogenous and interlinked set of technologies, instruments-related technologies are more loosely coupled. However, instruments appear to have a bridging function between the otherwise almost disconnected chemistry and digital technologies. In particular, optics can be found in a central position in between and connected to both, whereas measurement and medical technologies is more related to computer technology, and analysis of biological material to chemistry.

Figure 14. Technology field relationships in Neurotechnology within a technology space network

Note: Nodes = Technology Fields, Edges = Relatedness. Node and label size indicates complexity of technology field.

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Table 4 reports the specialization pattern of the five countries emerged as leading neurotechnology-related developments. Specialization is measured by the revealed technological advantage (RTA) of a technology field, whereby a value higher than 1 indicates that the share of a country's neurotechnology patents in a technology field is higher than the average share of the fields across all countries.²⁴ A value higher than one indicates that the considered country is relatively (hyper) specialized in that very technology compared to the others, whereas a zero value denotes no activity in the field. Consequently, low values close to zero denote relative less specialization.

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The revealed technological advantage (RTA) index is defined as a country's share of patents in a particular technology field divided by the country's share in all patent fields. The index is equal to zero when the country holds no patent in a given sector; is equal to 1 when the country's share in the sector equals its share in all fields (no specialization); and above 1 when a positive specialization is observed (OECD, 2015).

Table 4. Revealed Technological Advantage (RTA) in neurotechnology by top-countries and technology field

Technology Field	China	Germany	Japan	South Korea	United States
Computer technology	1.58	0.62	1.24	0.96	1.1
Medical technology	0.72	1.18	0.69	1.3	0.92
Pharmaceuticals	0.2	2.03	0.21	0.28	1.06
Control	0.54	0.76	0.74	0.86	1.13
Measurement	1.04	1.8	0.91	0.39	0.98
Organic fine chemistry	0.13	2.06	0.06	0.22	1.08
Biotechnology	0.7	1.72	0.41	0.86	0.76
Audio-visual technology	0.71	0.47	1.78	1.05	1.03
Optics	0.62	0.9	1.16	0.99	0.94
IT methods for management	1.24	0.09	0.54	1.91	1.01
Transport	0.32	1.82	0.83	2.16	0.86
Analysis of biological materials	1.11	2.44	0.31	1.2	0.72
Telecommunications	0.29	0.64	3.34	0.64	0.93
Furniture, games	1.01	0.1	0.7	1.24	1.04
Digital communication	0.94	0.42	1.35	1.23	0.97

RTA ≥ 1 RTA ≤ 0.5

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

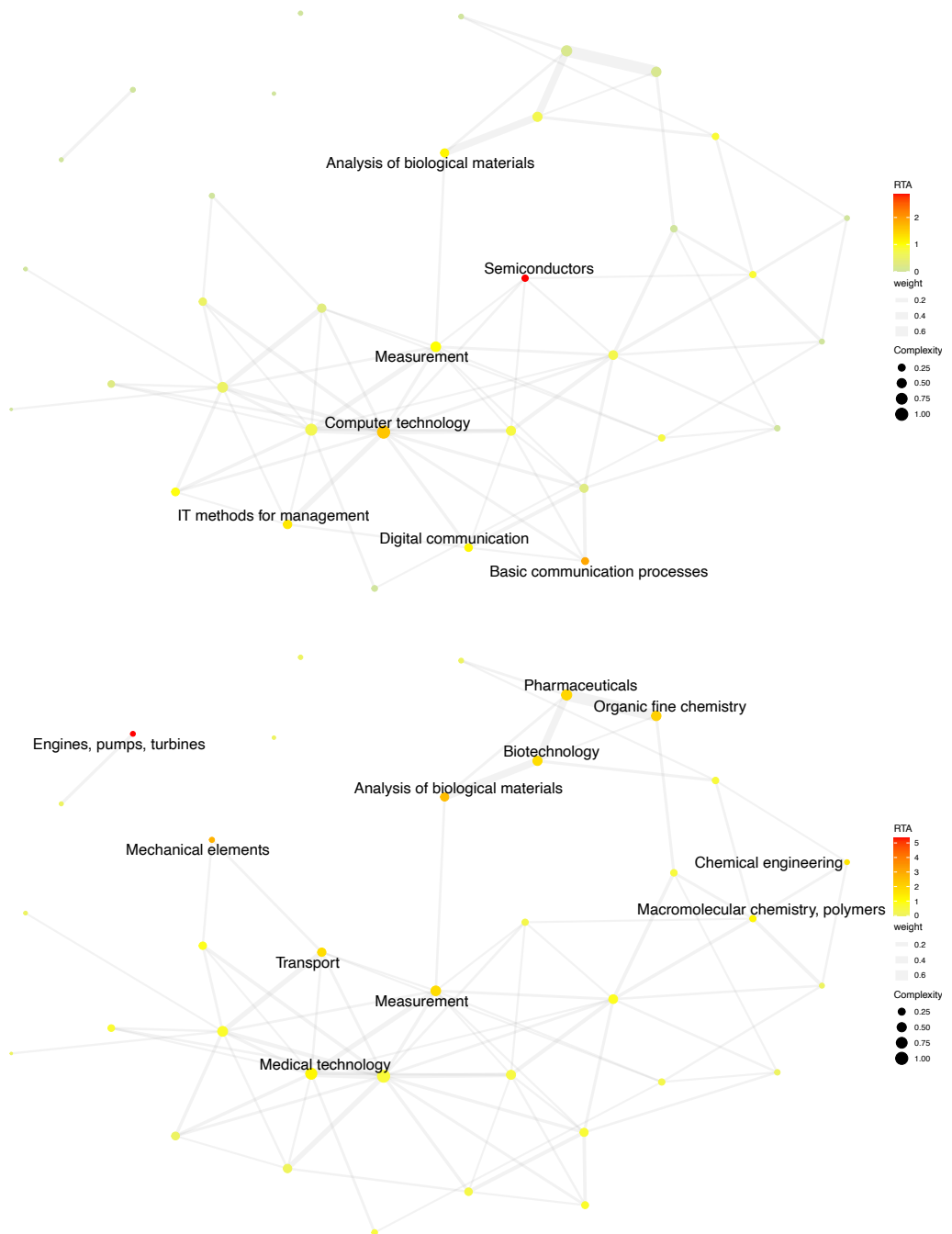
Notably distinctive patterns can be observed, whereby Germany tends to specialize in chemistry related technology fields (pharmaceuticals, biotechnology, organic fine chemistry etc.), whereas Asian countries, i.e. South Korea and China, tend to specialize in computer science and electrical engineering related technology fields (namely, computer technology, digital communication, audiovisual technologies etc.). China emerges to be the country most focused on applications of neurotechnology that leverage computer science-related fields. The United States conversely exhibit a hybrid specialization patterns, whereby both chemistry and computer science-related fields are leveraged in relation to neurotechnology.

BOX 7**Technological relatedness, complexity
and the technology space**

Relatedness, i.e. the state or fact of being related or connected, emerges when two or more activities, such as products, industries, or research areas, require similar knowledge or inputs (Balland *et al.*, 2022). In order to capture whether and to what extent innovation or research outputs are related to one another, one can look at the frequencies of co-occurrences. This can be measured by the times that different pairs of technology classes or scientific fields are mentioned together in a patent document or scientific article, respectively. This allows to shed light on how and how much different scientific and technology fields are leveraged together in order to give rise to new scientific outcomes or innovations. This in turn contributes to inform about the complexity of technological trajectories such as neurotechnology's ones and about the technology space they cover and rely upon. The intuition behind this method is that two technology fields that are frequently found together in the same patent application are related to each other's, in terms of knowledge inputs, functionality, or application.

We here rely on information about co-occurrences of technology fields within the same patent application to infer their relatedness. Applying a network mapping onto co-occurrences further allows revealing the structure of the overall technology space covered by neurotechnology-related developments. Inspecting the technology space allows, among others, to identify core technologies as well as corollary developments and, their relationships. Comparing the specialization pattern of countries in terms of co-occurrences further allows to shed light on the country-specific knowledge base and industry structure.

Figure 15 below illustrates such patterns of specializations in the neurotechnology space in relation to China (top) and Germany (bottom). This aims at highlighting different specialization pattern. An illustration of the technology space for the top-5 countries can be found in **Figure 19** in the appendix.

Figure 15. Neurotechnology space – China (top) and Germany (bottom)

Note: Nodes = Technology Fields, Edges = Relatedness. Node color indicates RCA, node size complexity of technology field. Only technology fields with RCA ≥ 1 are labeled.

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Important differences emerge not only in relation to the revealed technological advantage of the two countries, as already showed in **Table 4** above, but also in the way agents in those countries combine knowledge when it comes to innovating in the neurotechnology space. This in turn mirrors differences in factor conditions including the underlining technology policies and the human capital available, as well as in the very type of innovations that each one of these countries brings to the world.

Table 5 below goes more in details about the specific technological areas leveraged in neurotechnology patents, to provide concrete and detailed information about the type of industrially viable applications that are protected when patenting neurotech inventions. This is done by highlighting the most frequently used International Patent Classification (IPC) technology classes at the subgroup level referenced in neurotech patents. While shares may look small, one may need to remember that there are more than seventy thousand subgroups in the IPC and therefore the share mentioned below are non-negligible and help understand which specific technology or combinations thereof are used when innovating in the neurotech space. A total of 1,588 subgroups appears to have been referred to in the neurotech patents identified more than 10 times, where the distribution of subgroup occurrence is left skewed (few occur often, many occur very few times). Noteworthy, many of the most used ones relate to computing, including artificial intelligence approaches such as machine learning.

Table 5. Top 15 IPC classes in neurotechnology patents (subgroup level)

IPC Class	Description	Percent
G06N 3/08	Computer systems based on biological models ••• Learning methods	1.4
G06N 3/04	Computer systems based on biological models ••• Architecture, e.g. interconnection topology	1.4
G06K 9/62	Methods or arrangements for reading or recognizing printed or written characters or for recognizing patterns, e.g. fingerprints ••• Methods or arrangements for recognition using electronic means	1.3
C12N 15/09	Mutation or genetic engineering; DNA or RNA concerning genetic engineering, vectors, e.g. plasmids, or their isolation, preparation or purification ••• Recombinant DNA-technology	1.2
C12Q 1/68	Measuring or testing processes involving enzymes or microorganisms: ••• involving nucleic acids	1.2
A61K 38/00	Medicinal preparations containing peptides	1.1
G06K 9/00	Methods or arrangements for reading or recognizing printed or written characters or for recognizing patterns, e.g. fingerprints	1.0
A61P 25/00	Drugs for disorders of the nervous system	0.8
A61B 5/00	Measuring for diagnostic purposes	0.7
A61P 43/00	Drugs for specific purposes, not provided for in groups	0.6
A61P 25/28	Drugs for disorders of the nervous system ••• for treating neurodegenerative disorders of the central nervous system, e.g. nootropic agents, cognition enhancers, drugs for treating Alzheimer's disease or other forms of dementia	0.6
G06N 20/00	Machine learning	0.6
C12N 5/10	Undifferentiated human, animal or plant cells, e.g. cell lines; ••• Cells modified by introduction of foreign genetic material, e.g. virus-transformed cells	0.6
G06T 7/00	Image analysis	0.6
G01N 33/68	Investigating or analyzing materials by specific methods not covered by groups ••• involving proteins, peptides or amino acids	0.6

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

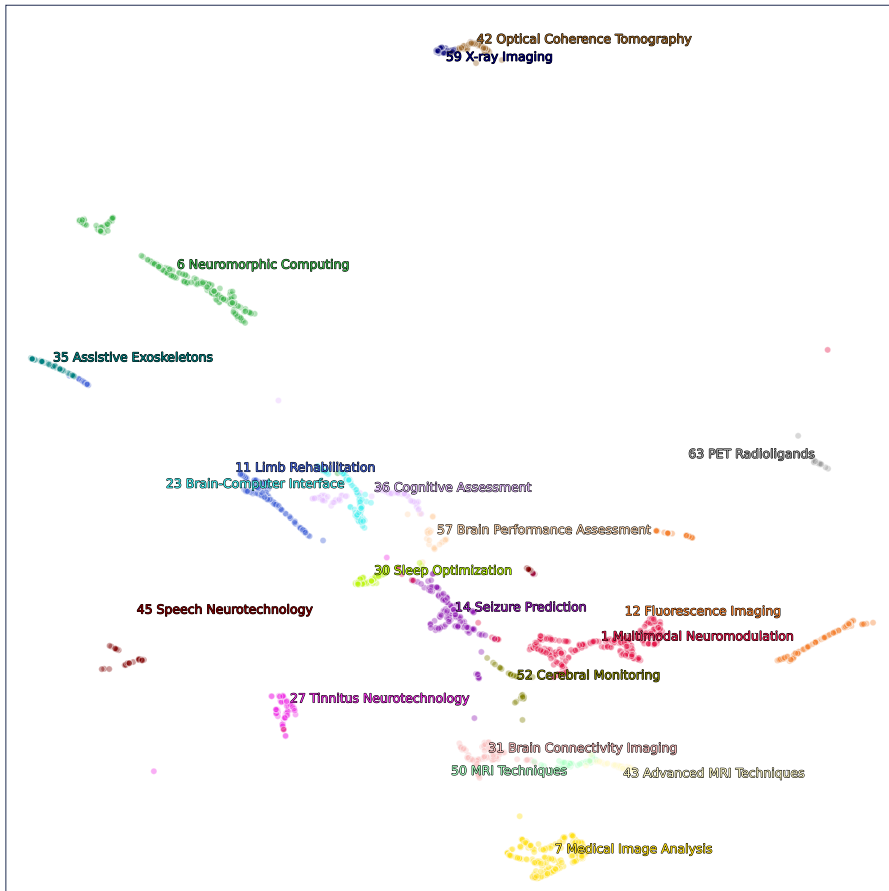
5.3 A closer look at neurotechnology patents

For a more nuanced understanding of the identified patent documents, we implement a clustering and topic identification process akin to the one used on scientific documents. To this end, we again leverage the PatentSBERTa patent embedding model for patent text representation. Given that keywords will only be used to interpret the topic rather than generating the queries, we opt for a simple term-count based keyword extraction from patent titles and abstracts. We then apply the cTF-IDF weighting to these keywords and IPC symbols to enhance our understanding of the identified topics and specific technology classes. This approach helps creating an initial IPC class taxonomy for neurotechnology-related patents and enables the calculation of prevalent technology class combinations at the broader section level (different letters in for IPC symbols in combinations).

For topic interpretation, we employ GPT-4, guided by keywords, predominant IPC symbols, and select example documents. Our goal is to pinpoint patent groups that correspond to recognized neurotechnology terminologies in Neuroimaging, Neurodevices, Brain Computer Interfaces, and the usage of Computational Methods and Artificial Intelligence in Neurosciences.

5.3.1 Identified technology topics in patents

In total, 67 coherent clusters are identified through the segmentation of patent titles and abstracts, as can be seen from **Table 8** in the Appendix. While many patents encompass neurotechnology or neuroscience functionalities, only 20 get rated 4 or 5 on a 1-5 scale by GPT-4. These are visualized in a in **Figure 16**, with the original text embeddings of the patents reduced from 768 to 2 dimensions for plotting. The visualization is optimized to be read as a geographical map: axes with marks that are plotted close by are similar in terms of their content.

Figure 16. Key technology topics identified in patents

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

The largest, coherent topic, termed "**Multimodal Neuromodulation**", comprises 535 patents detailing methodologies for deep or superficial brain stimulation designed to address neurological and psychiatric ailments. These patented technologies interact with various points in neural circuits to induce either Long-Term Potentiation (LTP) or Long-Term Depression (LTD), offering treatment for conditions such as obsession, compulsion, anxiety, depression, Parkinson's disease, and other movement disorders. The modalities encompass implanted deep-brain stimulators (DBS), Transcranial Magnetic Stimulation (TMS), and transcranial Direct Current Stimulation (tDCS). Among the most representative documents for this cluster are patents with titles: *Electrical stimulation of structures within the brain* or *Systems and methods for enhancing or optimizing neural stimulation therapy for treating symptoms of Parkinson's disease and or other movement disorders*.

The **"Seizure Prediction"** cluster, comprising 190 patents, presents another prominent theme within the realm of neurotechnology. This cluster primarily pertains to the real-time analysis of brain wave data, mainly using Electroencephalogram (EEG) or Electrocorticogram (ECoG) signals, with the aim of detecting and forecasting seizures and brain dysfunctions. The detection and prediction of these neurological events provide vital information for diagnosis or treatment of neurological disorders.

The technologies associated with these patents are primarily coded under specific International Patent Classification (IPC) codes, indicative of medical apparatus for diagnosis, antennas, and other apparatus for psychological testing or biofeedback. In essence, these classifications align with technologies involved in non-invasive neurodiagnostic tools and techniques, which form the basis of the patents in this cluster.

Examples of patents in this cluster include a *real-time brain wave analysis system and method using fast Fourier transform*, a *method for the prediction, rapid detection, warning, prevention, or control of changes in the brain states of a subject using Hurst parameter estimation*, and a *method for amplifying abnormal pattern signal in observed brain activity of a subject for diagnosis or treatment*. Each of these patents offers a unique approach towards the prediction and early detection of seizures, thereby underscoring the significant progress made in this facet of neurotechnology.

A cluster identified as **"Neuromorphic Computing"** consists of 366 patents primarily focused on devices designed to mimic human neural networks for efficient and adaptable computation. The principal elements of these inventions are resistive memory cells and artificial synapses. They exhibit properties similar to the neurons and synapses in biological brains, thus granting these devices the ability to learn and modulate responses based on rewards, akin to the adaptive cognitive capabilities of the human brain.

The primary technology classes associated with these patents fall under specific IPC codes, representing the fields of neural network models, analog computers, and static storage structures. Essentially, these classifications correspond to technologies that are key to the construction of computers and exhibit cognitive functions similar to human brain processes.

Examples for this cluster include *neuromorphic processing devices that leverage variations in resistance to store and process information*, *artificial synapses exhibiting spike-timing dependent plasticity*, and *systems that allow event-driven learning and reward modulation within neuromorphic computers*.

In relation to neurotechnology as a whole, the "neuromorphic computing" cluster holds significant importance. It embodies the fusion of neuroscience and technology, thereby laying the basis for the development of adaptive and cognitive computational systems. Understanding this specific cluster provides a valuable insight into the progressing domain of neurotechnology, promising potential advancements across diverse fields, including artificial intelligence and healthcare.

The **"Brain-Computer Interfaces"** cluster, consisting of 146 patents, embodies a key aspect of neurotechnology that focuses on improving the interface between the brain and external devices. The technology classification codes associated with these patents primarily refer to methods or

devices for treatment or protection of eyes and ears, devices for introducing media into, or onto, the body, and electric communication techniques, which are foundational elements of brain-computer interface (BCI) technologies.

Key patents within this cluster include a *brain-computer interface apparatus adaptable to use environment and method of operating thereof*, a *double closed circuit brain-machine interface system*, and an *apparatus and method of brain-computer interface for device controlling based on brain signal*. These inventions mainly revolve around the concept of using brain signals to control external devices, such as robotic arms, and improving the classification performance of these interfaces, even after long periods of non-use.

The inventions described in these patents improve the accuracy of device control, maintain performance over time, and accommodate multiple commands, thus significantly enhancing the functionality of BCIs.

Other identified technologies include systems for medical image analysis, limb rehabilitation, tinnitus treatment, sleep optimization, assistive exoskeletons, and advanced imaging techniques, among others.

Medical Image Analysis Technologies, for instance, leverage convolutional neural networks for enhancing various medical imaging modalities. This improvement in medical image analysis and diagnosis is achieved by enhancing image quality, segmenting structures, and providing medical recommendations based on machine learning classifiers.

Limb Rehabilitation technologies are examples of neurotechnology's therapeutic applications, utilizing augmented reality, brain-computer interfaces, and virtual reality to aid in gait and limb rehabilitation. This technology guides patients through exercises in virtual environments, provides feedback, and evaluates progress using electroencephalogram signals and motion sensors.

Furthermore, advancements in the treatment of specific conditions such as tinnitus and sleep disorders are evident with **Tinnitus Neurotechnology** and **Sleep Optimization** technologies. The former estimates uncomfortable loudness levels using electroencephalogram signals and provides tinnitus relief and hearing enhancement through synchronized electrical stimulation and sound enrichment. The latter focuses on improving sleep quality by creating personalized sleep classifiers based on biosignals and high-accuracy sleep studies.

Assistive Exoskeletons are another vital technological advancement, where electromyographic control and adjustable stiffness joints are used in exoskeletons to assist human movement and support the upper and lower limbs. These can be utilized for rehabilitation, mobility assistance, and support for individuals with physical disabilities or injuries.

Lastly, technologies such as **Advanced MRI Techniques** and **Optical Coherence Tomography**, represent innovations in neuroimaging. They use novel methods for improving spatial and temporal resolutions, reducing artifacts, tracking motion, and enabling real-time, three-dimensional imaging of biological tissues. This could potentially aid in medical diagnostics and treatment planning, showcasing the multifaceted impact of neurotechnology in the health sector.

Table 6 presents top patent applicants for a selected set of neurotechnology topics identified in patents.

Table 6. Top patent applicants, selected neurotechnologies

Technology	Company	Count
Neuromorphic Computing	Intel Corporation	20
	IBM Corporation	17
	French Alternative Energies and Atomic Energy Commission (CEA)	11
Multimodal Neuromodulation	Forschungszentrum Jülich GmbH	7
	Cyberonics, Inc.	5
	General Electric Company	4
Medical Image Analysis	Siemens Healthcare GmbH	14
	Ping An Technology (Shenzhen) Co., Ltd.	8
	General Electric Company	6
Limb Rehabilitation	National Yang Ming University	4
	Korea Advanced Institute of Science & Technology (KAIST)	3
	Cybermedic Co. Ltd.	2
Seizure Prediction	Cyberonics, Inc.	3
	Instrumentarium Corporation	2
	IctalCare AS	2

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Table 9 in Appendix presents examples of patent application titles of neurotechnology topics in the above-mentioned areas.

5.3.2 A proposed IPC-based taxonomy of neurotechnology-related patents

In our analysis, we've developed a provisional IPC-based taxonomy for neurotechnology by curating a highly filtered sample of neurotechnology patents (described above – clusters with a 4 or 5 score as indicated by GPT-4). Utilizing the cTF-IDF method, we can extract the most representative IPC codes in each cluster, rather than only listing most common codes. This not only helps understand the breadth and multidisciplinary nature of this expansive technological

field, but offers an initial framework for its delineation, aiding in its mapping, classification, and monitoring. The proposed IPC-based taxonomy of Neurotechnology-related patents can be found in **Table 10** in the Appendix.

The most prominent groups identified include A61B 5/00, G01R 33/00, and G01T 1/00, all relating to measurement technology. Furthermore, G06N 3/00, which concerns computer systems modelled on biological structures, and G16H 30/00, 50/00, pertaining to information technology, also emerge.

Overall following technologies are identified. A detailed list of IPC codes can be found in the Appendix.

- ▶ **Medical Imaging:** Technologies include nuclear magnetic resonance imaging (MRI), computerised tomographs, and various forms of spectroscopy.
- ▶ **Physiological Measurement:** These include devices for measuring characteristics of blood, heart rate, pulse, body temperature, bioelectric signals, cerebral pressure, respiratory organ functions, and movement of body parts.
- ▶ **Neurological Technologies:** They include neurostimulation, measuring bioelectric signals, electroencephalography, electrodes, and devices specifically for treating neurodegenerative disorders.
- ▶ **Surgical Technologies:** These include surgical robots, apparatuses for positioning patients, devices for correcting stammering, and devices related to orthopedic needs, such as splints, casts, and braces.
- ▶ **Audiology:** Technologies like audiometers and devices to help ear patients replace auditory perception.
- ▶ **Biomaterial Analysis:** Techniques for analyzing biological material, such as blood and urine, often involving biospecific ligand binding methods or radiolabeled substances. Also includes recombinant DNA-technology and handling medical images.
- ▶ **Bioelectric Control:** Myoelectric control devices and systems associated with electromagnets and the implantation of stimulators.
- ▶ **Pharmaceuticals:** Including alcohols, phenols, organic compounds, and halogens.
- ▶ **Health Monitoring Systems:** Devices for tracking sleep condition, measuring muscular strength, measuring movement of the body, and monitoring cardiovascular and respiratory conditions.
- ▶ **Speech Recognition:** Technologies include speech recognition using non-acoustical features, segmentation, word boundary detection, and recognition of special voice characteristics.
- ▶ **Artificial Intelligence:** AI systems that simulate biological cells, neural network models, learning methods, architecture, and region-based segmentation, often used for electronic clinical trials, handling medical images, or health risk assessment.

- ▶ **Nuclear Technologies:** Devices involving nuclear magnetic resonance or those utilizing radioactive labeled substances.
- ▶ **Optical Technologies:** Use of optical sensors, interferometry, absorption spectrometry, fluorescence, phosphorescence, and scattering for measuring and testing.
- ▶ **Computer Interaction:** Arrangements for interaction between users and computers, particularly those involving living beings or their nervous systems.

5.3.3 Prominent IPC Combinations in Neurotech Patents

Utilizing a preliminary taxonomy formed from IPC symbols of selected patents, we identified unique technology clusters within the neurotechnology domain. In this section, our focus shifts to investigating the most common combinations of IPC codes at the group level, represented by the first four characters of the IPC symbol. The analysis specifically relates to patents that have more than one IPC code, where the paired codes fall into different sections (different initial letters). Our analysis is limited to a selection of patents unambiguously classified under neurotechnology, as detailed in section 5.3.1 *Identified technology topics in patents*. Considering the vast number of codes at this level (7590 as per the 2023 IPC Publication), it is not highly probable to find high occurrence counts of combinations within our narrowly defined sample. Consequently, our ensuing analysis provides a more qualitative interpretation of the identified combinations.

IPC code A61B 5/00, related to physiological measurement technology, was prominent, pairing with codes for optical elements (G02B 6/00), semiconductor devices (H01L 21/00), wireless power supply circuits (H02J 50/00), and vehicle accommodations (B60N 2/00). This pattern demonstrates the broad use of physiological measurements across various applications, reflecting neurotechnology's versatility.

Neurostimulation technology (A61N 1/00) frequently intersects with health informatics (G16H 50/00), similar to the pattern observed with A61B 5/00 and G16H 30/00. These pairings highlight the crucial role of informatics and data analysis in physiological measurements and neurostimulation.

Artificial intelligence technology (G06N 3/00) combines with codes for devices using magnetic effects (H01L 43/00), capacitors (H01G 9/00), and radiation therapy (A61N 5/00), indicating AI's integration in diverse neurotech applications.

IPC codes for medical imaging like G06T 7/00, G01N 21/00, and G01R 33/00 pair repeatedly with A61B 5/00, pointing to the heavy reliance on imaging and material analysis in physiological measurements.

Finally, the repetition of pharmaceutical-related IPC codes (C07D 211/00, C07B 59/00, C07D 217/00, C07D 215/00) with A61K 47/00, A61K 51/00, and G01N 33/00 suggests a growing intersection between pharmaceutical technology and biomaterial analysis, medications, and pharmaceutical preparations.

Neurotechnology's multifaceted nature is reflected in the above IPC combinations, representing the convergence of AI, medical imaging, informatics, pharmaceuticals, and various physiological measurement techniques. These identified combinations provide an understanding of the complex neurotechnology landscape and aid future patent landscaping and monitoring efforts.

An exhaustive list of IPC combinations is included as **Table 11** the Appendix.

6.

Some first
conclusions to inform
the neurotechnology
policy debate

Neurotechnology is a complex and rapidly evolving technological paradigm whose trajectories have the power to shape people's identity, autonomy, privacy, sentiments, behaviors and overall well-being, i.e. the very essence of what it means to be human.

Designing and implementing careful and effective norms and regulations ensuring that neurotechnology is developed and deployed in an ethical manner, for the good of individuals and for society as a whole, call for a careful identification and characterization of the issues at stake. This entails shedding light on the whole neurotechnology ecosystem, that is what is being developed, where and by whom, and also understanding how neurotechnology interacts with other developments and technological trajectories, especially AI. Failing to do so may result in ineffective (at best) or distorted policies and policy decisions, which may harm human rights, fundamental freedoms and human dignity.

Addressing the need for evidence in support of policy making, the present report offers first time robust data and analysis shedding light on the neurotechnology landscape worldwide. To this end, it proposes and implements an innovative approach that leverages artificial intelligence and deep learning on data from scientific publications and patents to identify scientific and technological developments in the neurotech space. The methodology proposed represents a scientific advance in itself, as it constitutes a quasi-automated replicable strategy for the detection and documentation of neurotechnology-related breakthroughs in science and innovation, to be repeated over time to account for the evolution of the sector. Leveraging this approach, the report further proposes an IPC-based taxonomy for neurotechnology which allows for a structured framework to the exploration of neurotechnology, to enable future research, development and analysis. The innovative methodology proposed is very flexible and can in fact be leveraged to investigate different emerging technologies, as they arise.

The findings of this report point to a significant growth of the neurotechnology sector over the last two decades, as mirrored by the substantial and increasing investments made by both the public and private sectors and the growing number of publications and patents. Such progress nevertheless appears very unequal, with only a few countries emerging as the primary driving force behind these advancements.

In terms of technological trajectories, we uncover a shift in the neurotechnology industry, with greater emphasis being put on computer and medical technologies in recent years, compared to traditionally dominant trajectories related to biotechnology and pharmaceuticals. This shift warrants close attention from policymakers, and calls for attention in relation to the latest (converging) developments in the field, especially concerning AI-related methods and applications and neurotechnology.

This is even more important as the observed growth and specialization patterns are unfolding in the context of regulatory environments that, generally, are either not existent or not fit for purpose. Given the sheer implications and impact of neurotechnology on the very essence of human beings, this lack of regulation poses key challenges related to the possible infringement of mental integrity, human dignity, personal identity, privacy, freedom of thought, and autonomy,

among others. Furthermore, issues surrounding accessibility and the potential for neurotech enhancement applications triggers significant concerns, with far-reaching implications for individuals and societies.

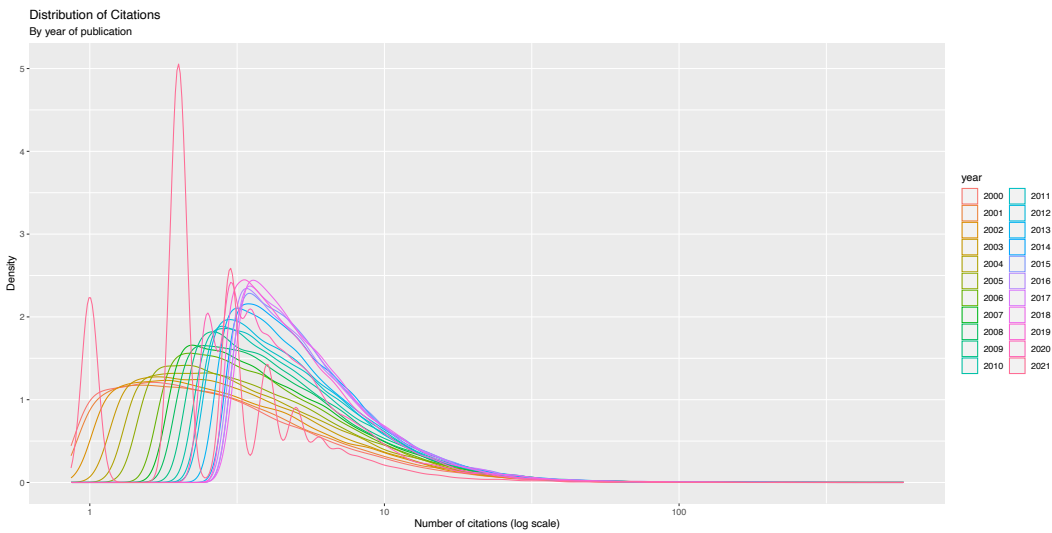
This is why we believe the present report represents a first important step in the quest for the ethical and human rights-centered development and policy framing of powerful technologies like neurotechnology. Einstein is quoted as having said “If I had an hour to solve a problem, I’d spend 55 minutes thinking about the problem and five minutes thinking about solutions”. This report is part of the 55 minutes careful definition of the problem and aims to encourage more analysis in relation to neurotechnology, at the same time as it proposes solid evidence. This shall allow policymakers gaining a better understanding of the state-of-the-art of the global neurotechnology landscape and help propose carefully designed, effective solutions and decide how to best move forward, for the sake of humankind.

Evidently, like all reports, the present contribution does not represent the last word about neurotechnology, nor is perfect. It is the beginning of an international and interdisciplinary evidence-gathering effort. For example, if we were to consider all patents, and not only IP5 patents, or scientific articles published also in languages other than English, we would have a (partially) different picture of the neurotech landscape. We leave this and other analytical and operational efforts to future research. For the moment we concentrate on providing an accurate picture of overall neurotechnology developments, and in particular those that could enter our life already, everywhere in the world, given their importance and practical applicability.

This understanding aims to support policy decisions about the governance of neurotechnology, and UNESCO’s efforts to devise an international ethical framework for the governance of neurotechnology, a levelling the global playing field tool fostering a responsible, equitable, and respectful neurotechnology that has human rights, fundamental freedoms and human dignity at its core.

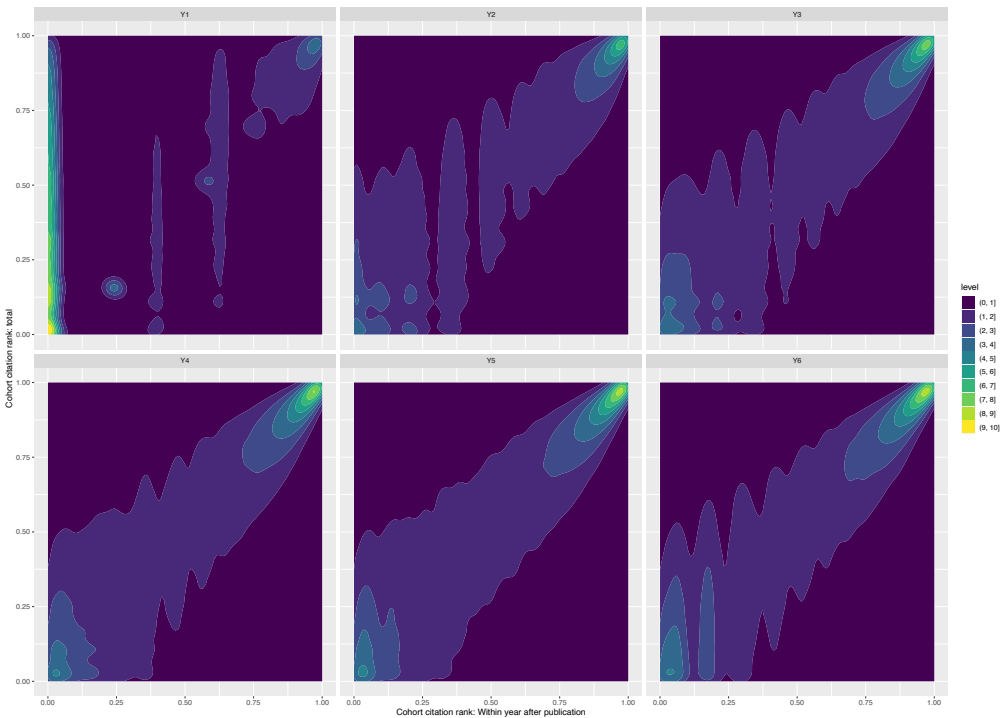
Appendix

Figure 17. Number of citations by neuroscience publication cohort



Source: authors' own compilation on data from Scopus (2000-2021)

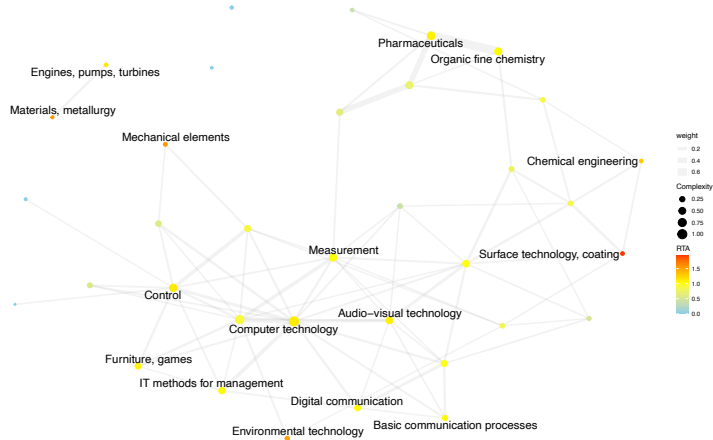
Figure 18. Citation rank density of neuroscience publications: total vs. year 1-6 after publication



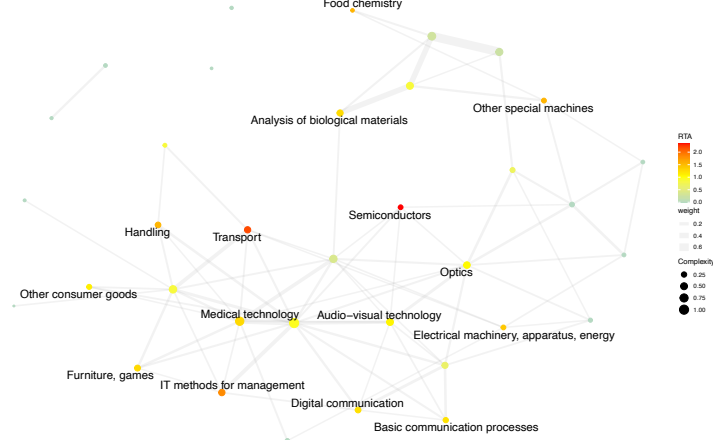
Source: authors' own compilation on data from Scopus (2000-2021)

Figure 19. Technology spaces for the top-5 Neurotechnology developing countries

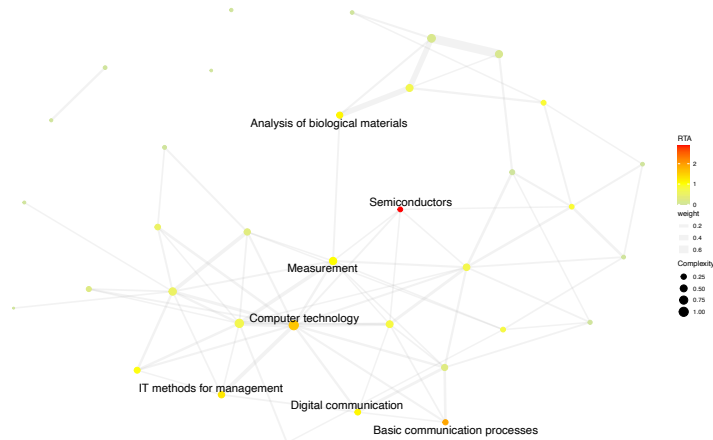
US



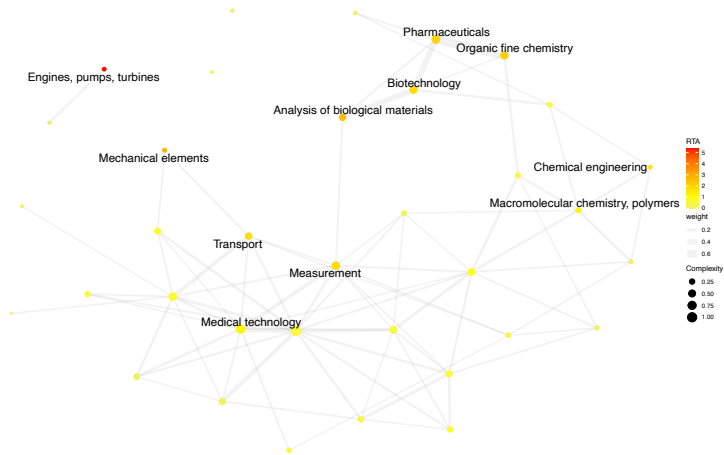
KR



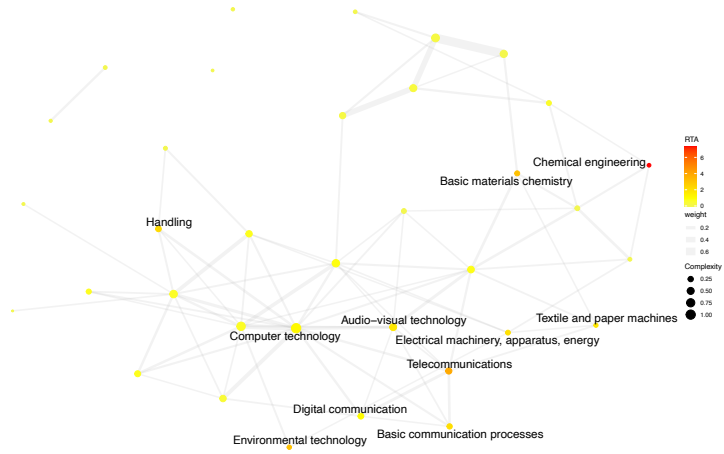
CN



DE



JP



Note: Nodes = Technology Fields, Edges = Relatedness. Node color indicates RCA, node size complexity of technology field. Only technology fields with RCA ≥ 1 are labeled.

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Table 7. Topics identified in the neuroscience corpus

Topic	Label	Summary	Application	Size
1	Fragile X Syndrome	Investigation of Fragile X syndrome (FXS) and its underlying molecular mechanisms, using Fmr1 KO mice as a model system.	Understanding the role of FMRP in FXS and developing potential therapeutic interventions for FXS and related neurodevelopmental disorders.	63
2	STN DBS	Deep brain stimulation (DBS) of the subthalamic nucleus (STN) for treating Parkinson's disease and other movement disorders.	DBS is used to alleviate motor symptoms in Parkinson's disease, essential tremor, dystonia, and OCD by targeting the basal ganglia and modulating oscillatory activity.	169
3	Cochlear Implants	The topic focuses on tinnitus, cochlear damage, and hearing loss caused by noise exposure, and the use of cochlear implants to improve hearing and speech perception.	Cochlear implants are used to restore hearing in individuals with cochlear damage and hearing loss, improving speech recognition and auditory processing.	150
4	Auditory Hair Cells	The topic focuses on the role and function of hair cells in the auditory system, specifically in the cochlea, and their involvement in hearing loss and deafness.	Neurotechnology applications in this area include the development of therapeutic approaches to restore or improve hearing function and the study of hair cell regeneration.	65
5	Migraine Research	Investigation of migraine pathophysiology and potential treatment options.	Understanding the role of CGRP in migraine pathophysiology and exploring potential treatments such as erenumab, sumatriptan, and onabotulinumtoxinA.	141
6	Neuropathic Pain Mechanisms	Investigation of neuropathic pain mechanisms and the role of ion channels in sensory neurons and spinal cord.	Understanding and potentially modulating neuropathic pain through targeting ion channels and sensory neurons involved in pain perception and transmission.	526
7	Bilingualism Neuroimaging	Investigation of neural correlates and cognitive control processes in bilingual individuals using functional neuroimaging techniques.	Understanding the neural basis of bilingualism and its effects on cognitive control, language switching, and brain plasticity.	66
8	Retinal Photoreceptors	Investigation of retinal photoreceptors, their organization, and their role in vision and circadian rhythms.	Understanding retinal photoreceptors can lead to advancements in visual information processing and potential treatments for retinal disorders.	84

Topic	Label	Summary	Application	Size
9	Microelectrode Arrays	Microelectrode arrays are used for recording and stimulating neural activity, with challenges in minimizing tissue damage and immune response.	These arrays are utilized in various neurotechnology applications, such as recording neural signals, stimulating neural circuits, and monitoring brain function.	72
10	Numerical Cognition	Investigating the neural basis of numerosity, arithmetic, and number processing in the intraparietal sulcus and left angular gyrus.	Understanding dyscalculia and developing targeted neurostimulation interventions for improving mathematical abilities.	101
11	IBS Neurogastroenterology	Investigation of the enteric nervous system and its relationship with irritable bowel syndrome (IBS) symptoms, intestinal microbiota, and visceral hypersensitivity.	Understanding the role of the enteric nervous system in IBS can lead to targeted neurotechnology interventions for symptom management and improved quality of life.	69
12	Ophthalmology, Corneal Treatments	Ophthalmology and corneal treatments	Corneal treatments and surgeries, such as LASIK, PRK, and keratoplasty, are used to address various eye conditions like keratoconus, dry eye, and myopia.	228
13	Epilepsy Surgery Neuroimaging	Epilepsy surgery and related neuroimaging techniques for seizure control in drug-resistant focal epilepsy.	Utilizing MRI, FDG-PET, and DBS electrodes for presurgical evaluation, seizure focus identification, and resective surgery in intractable epilepsy cases.	88
14	Ocular Refractive Errors	The topic revolves around the study and management of refractive errors in the eye, such as myopia, hyperopia, and astigmatism.	Neurotechnology applications in this context may include the use of advanced imaging techniques for ocular biometry and corneal topography, as well as the development of vision correction devices like contact lenses and spectacles.	66
15	Ophthalmology Procedures	Ophthalmology-related procedures and measurements focused on eye conditions and surgeries.	Assessment and treatment of eye conditions such as cataracts, glaucoma, and myopia through surgeries like LASIK and phacoemulsification.	131

Topic	Label	Summary	Application	Size
16	Retinal Regeneration	The topic focuses on retinal ganglion cells (RGCs), Müller glia, and their role in axon regeneration and optic nerve injury.	Neurotechnology applications include promoting RGC survival and regeneration after optic nerve injury, and transplantation of retinal progenitor cells to restore visual function.	54
17	Memristor Neural Networks	Investigation of memristor-based recurrent neural networks and their synchronization using numerical simulations and Lyapunov functional methods.	Improving stability and synchronization in neural networks, potentially leading to advancements in brain-inspired computing and control systems.	66
18	Neural Network Stability	Investigation of stability and synchronization in neural networks with time-varying delays using numerical simulations and Lyapunov stability theory.	Improving the stability and synchronization of neural networks in closed-loop control systems and complex networks.	172
19	Retinal Neuroprotection	Neurotechnology for retinal diseases and glaucoma	Neurotechnology applications in this context include neuroprotection, prevention of retinal degeneration, and reducing inflammation in retinal diseases such as glaucoma, diabetic retinopathy, and age-related macular degeneration.	138
20	Epigenetics, Memory, Neurology	Exploration of epigenetic mechanisms and their role in memory formation, consolidation, and neurological disorders.	Understanding and potentially manipulating epigenetic processes to improve memory and treat neurological disorders.	72
21	Intravitreal Therapy	Intravitreal injections of anti-VEGF agents for treating retinal disorders.	Improving visual acuity and managing conditions such as age-related macular degeneration, diabetic macular edema, and retinal vein occlusion.	85
22	Ophthalmic Neurotechnology	Neurotechnology applications in vision and ophthalmology, focusing on optical coherence tomography angiography (OCTA) and related techniques for assessing retinal and choroidal health.	OCTA and related techniques are used to diagnose and monitor conditions such as age-related macular degeneration (AMD), diabetic retinopathy (DR), and glaucoma by measuring retinal thickness, vessel density, and other parameters.	265

Topic	Label	Summary	Application	Size
23	Gut-Brain Axis	Exploring the relationship between gut microbiota and various neurological and psychiatric disorders.	Investigating the effects of probiotics and prebiotics on gut microbiota composition and their potential role in modulating gut-brain axis communication, which may influence neurodevelopmental and psychiatric disorders.	206
24	Zebrafish Neurodevelopment	Investigating the effects of maternal immune activation and environmental factors on neurodevelopment and behavior using zebrafish models.	This research can help understand the underlying mechanisms of neurodevelopmental disorders like autism and schizophrenia, and potentially inform the development of interventions or preventive measures.	176
25	Automated Driving Neuroergonomics	Investigating human factors and ergonomics in highly automated driving using neurotechnology.	Using EEG and other neuroimaging methods to assess mental workload, fatigue, and cognitive load in driving simulators and real-world environments.	98
26	Plant Biology	Plant growth and development processes with a focus on auxin and plant immunity.	Not applicable for neurotechnology.	295
27	Brain Tumor Genomics	Analysis of genetic alterations and molecular subgroups in brain tumors for diagnosis and treatment strategies.	Utilizing molecular analysis and DNA sequencing techniques to identify specific genetic alterations and molecular subgroups in brain tumors, aiding in diagnosis and informing treatment strategies.	159
28	Virology Study	This topic focuses on the study of SARS-CoV-2 and other viruses, their replication, infection mechanisms, and host immune response.	Not applicable for neurotechnology.	227
29	COVID-19 Prediction	COVID-19 pandemic modeling and prediction using machine learning algorithms.	Machine learning algorithms are used to predict the spread of COVID-19, forecast the impact of interventions, and inform public health policies.	68

Topic	Label	Summary	Application	Size
30	Inflammation, Cardiovascular, Joints	Inflammatory response and cellular mechanisms in cardiovascular and joint diseases.	Investigating the role of inflammatory cytokines and cellular processes in the pathogenesis of cardiovascular and joint diseases, and potential therapeutic targets.	54
31	Epilepsy Detection	Automatic seizure detection and diagnosis of epilepsy using EEG signals and machine learning methods.	Classifying and detecting epileptic seizures from EEG signals using machine learning algorithms and deep learning approaches, such as CNNs, for improved diagnosis and clinical applications.	87
32	Muscle Mitochondrial Function	Exploration of the role of PGC-1 in skeletal muscle development and function, with a focus on mitochondrial biogenesis and related processes.	Understanding the molecular mechanisms behind muscle development and function, which could potentially inform the development of therapies for muscle-related disorders.	74
33	Deep Learning Neuroimaging	Using spiking neural networks and convolutional neural networks for medical image analysis and classification of brain tumors.	This neurotechnology involves the application of deep learning models, specifically spiking neural networks (SNNs) and convolutional neural networks (CNNs), for the diagnosis and prognosis of brain tumors through medical image analysis and classification.	110
34	Emotion Analysis	Neural network-based sentiment analysis and emotion recognition	Utilizing deep learning algorithms and neural networks for sentiment analysis and emotion recognition in human-computer interaction and social networks.	50
35	TBI Astrocyte Pathology	Investigation of the role of astrocytes in traumatic brain injury (TBI) and its associated pathologies, such as neuroinflammation, neurodegeneration, and epilepsy.	Understanding the cellular mechanisms involved in TBI can lead to improved diagnostic methods and potential therapeutic interventions for TBI-related conditions.	59
36	Ecosystem	Assessing biodiversity and ecosystem conservation.	Not applicable for neurotechnology	120
37	Antibiotic Resistance	The topic focuses on antibiotic resistance, biofilm formation, and the role of innate immunity in combating microbial pathogens.	This is mainly related to understanding antibiotic resistance mechanisms and the role of the immune system in fighting infections.	101

Topic	Label	Summary	Application	Size
38	Appetite Regulation	Investigation of the role of hormones and neuropeptides in regulating food intake, energy balance, and obesity through interactions with the hypothalamus and other brain regions.	Understanding the neural mechanisms behind appetite regulation and energy homeostasis can lead to the development of novel neurotechnology-based interventions for obesity and related metabolic disorders.	266
39	ANN Optimization	Optimization of artificial neural networks using evolutionary algorithms.	Improving the performance of artificial neural networks by optimizing their parameters and configurations using genetic algorithms and particle swarm optimization.	50
40	ML Classification	Machine learning techniques for classification and prediction using support vector machines and extreme learning machines.	These techniques can be applied to various neuroscience problems, such as predicting neural activity or classifying brain states based on neuroimaging data.	250
41	Deep Learning Vision	Deep learning-based computer vision and feature detection in images using Convolutional Neural Networks (CNN).	Improves image recognition, segmentation, and saliency detection for various domains such as face recognition and visual inspection.	57
42	CNN Neuroimaging	Deep learning and convolutional neural networks (CNNs) for image classification and object recognition.	CNNs are used for various neurotechnology applications such as feature extraction, detection, and classification in neuroimaging data.	87
43	Regenerative Medicine	The topic focuses on cellular processes and signaling involved in wound healing, bone formation, and stem cell differentiation.	This is relevant to regenerative medicine and understanding the mechanisms behind tissue repair and bone development.	218
44	Evolutionary Genetics	Exploration of genetic and evolutionary processes in species diversification and adaptation.	Understanding genetic variation and evolutionary mechanisms can inform conservation efforts and species management.	167
45	Gut Microbiota Analysis	Exploration of gut microbiota and its impact on host organisms.	Understanding the role of gut microbiota in health and disease, and developing computational tools for analyzing microbial communities.	143

Topic	Label	Summary	Application	Size
46	Huntington's Disease	Huntington's disease (HD) is a neurodegenerative disorder characterized by the progressive degeneration of striatal neurons due to mutant huntingtin protein.	Neurotechnology applications in HD research include neuroimaging for monitoring disease progression and deep brain stimulation for symptom management.	104
47	Not neurotechnology	Bacterial infections and immune response	Not applicable as the keywords are related to microbiology, immunology, and bacterial infections, not neurotechnology.	99
48	Molecular Biology	The topic focuses on the role of various molecular factors and processes in cell cycle progression, gene expression regulation, and cancer development.	This topic does not have a direct neurotechnology application, as it primarily deals with molecular biology and cellular processes related to cancer and gene regulation.	87
49	Cellular Senescence	Investigation of cellular senescence and signaling pathways in relation to aging and cancer.	Understanding cellular senescence mechanisms and signaling pathways can contribute to the development of potential therapies for age-related diseases and cancer.	392
50	Cell Death Mechanisms	Cellular processes involving apoptosis, autophagy, and exosomes.	Understanding cell death mechanisms and potential therapeutic targets.	58
51	Cellular Processes	Keywords focus on cellular organelles, membranes, and processes related to cellular homeostasis and stress responses.	These keywords do not directly relate to neurotechnology applications.	292
52	Cancer Biology	Cancer-related cellular processes and treatments	The keywords provided are mostly related to cancer biology, cellular processes, and treatments, with limited direct neurotechnology applications.	84
53	Cancer research	Cancer-related molecular mechanisms and biomarkers	Not applicable for neurotechnology	327
54	Protein Computational Analysis	Computational analysis of protein structures and interactions for drug discovery and understanding cellular processes.	Predicting protein function, identifying potential drug targets, and understanding complex biological systems.	194

Topic	Label	Summary	Application	Size
55	miRNA Regulation	The topic focuses on the role and function of microRNAs (miRNAs) in gene regulation and RNA silencing.	Understanding miRNA function and biogenesis can contribute to the development of gene therapies and targeted treatments for neurological disorders.	53
56	RNA Mechanisms	Exploration of RNA-related processes and their role in gene regulation and expression.	Understanding RNA mechanisms can contribute to the development of gene therapies and targeted treatments for various diseases.	145
57	TBI Neuro-technology	Investigation of the neurological consequences and potential neurotechnology interventions for traumatic brain injuries and related conditions.	Utilizing neuroimaging techniques and neuroprotective strategies to diagnose, monitor, and potentially treat traumatic brain injuries, chronic traumatic encephalopathy, and related neurodegenerative disorders.	69
58	DNA Repair	The topic focuses on DNA damage, repair mechanisms, and genome integrity.	This topic does not have direct neurotechnology applications as it primarily deals with molecular biology and DNA repair mechanisms.	106
59	Chromatin, Gene Regulation	Exploration of chromatin organization and gene regulation mechanisms.	Understanding gene expression and transcription processes, potential implications for neurodevelopment and neurological disorders.	154
60	Neural Circuit Visualization	Visualizing and tracing neural circuits using fluorescent proteins and viral vectors.	This approach enables the monitoring and mapping of neural connectivity, as well as the study of gene expression and cellular morphology in various brain regions.	59
61	Visual Cortex Plasticity	Investigation of visual cortex plasticity and the effects of visual deprivation on ocular dominance and experience-dependent plasticity in mice.	Understanding the mechanisms of visual cortex plasticity and sensory deprivation can inform the development of neurotechnology for vision restoration and enhancement.	52
62	Olfactory Dysfunction	Investigating the relationship between olfactory dysfunction and neurodegenerative diseases, particularly in the context of COVID-19.	Assessing olfactory function to detect early signs of neurodegenerative diseases and understanding the impact of COVID-19 on olfactory dysfunction and cognitive impairment.	104

Topic	Label	Summary	Application	Size
63	Olfactory Processing	Investigation of olfactory system and odor processing in various organisms, including insects and <i>C. elegans</i> .	Understanding olfactory processing can lead to the development of neurotechnologies for odor detection and artificial olfactory systems.	276
64	Optogenetics	Optogenetics is a neuroscience technique that uses light to control and monitor neural activity with high precision.	Optogenetics allows researchers to manipulate and observe neural circuits in real-time, enabling the study of neural functions, information processing, and behavioral responses in various organisms.	141
65	Neocortical Circuits	Investigation of neural circuits and synaptic plasticity in the neocortex, focusing on the interplay between excitatory and inhibitory neurons, and their role in sensory processing and motor control.	Understanding the principles of neural circuit organization and plasticity can lead to the development of targeted neurostimulation techniques and neuroprosthetics for sensory and motor rehabilitation.	564
66	BDNF, Plasticity, Learning	Exploration of BDNF-TrkB signaling and its role in synaptic plasticity, neuronal development, and learning.	Understanding BDNF-TrkB signaling can help develop neurotechnology for enhancing synaptic function and memory formation.	50
67	SCN Circadian Regulation	Investigation of the suprachiasmatic nucleus (SCN) and its role in regulating circadian rhythms and clock genes.	Understanding and potentially manipulating circadian rhythms for improved sleep, mental health, and metabolic regulation.	50
68	Brain Energy Metabolism	Investigation of brain energy metabolism and the role of astrocytes, glucose, and lactate in maintaining neuronal function.	Understanding the mechanisms of brain energy metabolism can help develop neuroprotective strategies for conditions like ischemia and epilepsy.	56
69	Sleep Memory Consolidation	Investigating the role of sleep in memory consolidation and the impact of sleep stages on learning and memory processes.	Optogenetics and acoustic stimulation can be used to modulate sleep stages and spindle activity, potentially enhancing memory consolidation and learning.	123
70	Sleep Neuro-technology	Investigation of sleep disorders and their impact on health using neurotechnology.	Monitoring and analyzing sleep patterns, disturbances, and disorders using techniques such as polysomnography and actigraphy to improve sleep health and daytime functioning.	363

Topic	Label	Summary	Application	Size
71	Purkinje Synaptic Plasticity	Investigation of Purkinje cells, their synaptic plasticity, and their role in cerebellar learning and motor functions.	Understanding the mechanisms of cerebellar learning and motor functions, potentially leading to improved treatments for motor disorders.	59
72	Astrocyte Function	Investigation of astrocytes and their role in neuronal activity, synaptic transmission, and glutamate regulation.	Understanding astrocyte function could lead to the development of neurotechnologies targeting glial cells for improved neuronal communication and treatment of neurological disorders.	114
73	Endocannabinoid System	The topic revolves around the endocannabinoid system, its receptors, and their role in synaptic transmission and plasticity.	Understanding the endocannabinoid system can help in developing neurotechnology for modulating synaptic transmission and treating neurological disorders.	73
74	Oxidative Stress, Mitochondria, Neurodegeneration	The topic revolves around oxidative stress, mitochondrial dysfunction, and ROS production in relation to neurodegeneration and aging.	Neurotechnology applications in this context could involve monitoring and targeting mitochondrial dysfunction and oxidative stress to prevent or treat neurodegenerative diseases.	68
75	Synaptic Plasticity	Investigation of synaptic plasticity, long-term potentiation (LTP), and long-term depression (LTD) in relation to learning and memory.	Understanding the molecular mechanisms underlying synaptic plasticity, LTP, and LTD can contribute to the development of neurotechnology targeting memory enhancement and treatment of cognitive disorders.	818
76	GABA, Memory, Plasticity	Investigation of GABA receptors and their role in synaptic plasticity, memory formation, and neuronal excitability.	Understanding the mechanisms behind memory formation and neuronal signaling, potentially leading to treatments for psychiatric and neurological disorders.	55
77	Spatial Memory	Investigation of grid cells, place cells, and hippocampal neurons for understanding spatial memory and navigation.	Understanding the role of hippocampal and entorhinal cortex neurons in spatial memory and navigation, which can potentially lead to the development of neurotechnologies for memory enhancement and treatment of memory-related disorders.	146

Topic	Label	Summary	Application	Size
78	Epilepsy Neurotechnology	Exploration of neurotechnology applications in epilepsy management and seizure control.	Neurotechnology applications in epilepsy include seizure detection and prediction devices, as well as deep brain stimulation and vagus nerve stimulation for seizure control.	230
79	fMRI, epilepsy, anesthesia	Investigating the relationship between brain activity, connectivity, and consciousness in epilepsy and anesthesia using functional magnetic resonance imaging (fMRI).	Identifying epileptogenic zones and understanding the effects of anesthesia on brain function and consciousness, potentially improving treatment and monitoring of epilepsy and anesthesia.	104
80	Exercise Neurogenesis	The topic explores the relationship between physical exercise, particularly voluntary wheel running, and its effects on neurogenesis, BDNF levels, and cognitive functions in the hippocampus.	This neurotechnology theme investigates how voluntary exercise can enhance adult hippocampal neurogenesis, BDNF expression, and improve learning and memory, potentially offering insights for combating age-related cognitive decline and depression.	61
81	Diet, Exercise, Cognition	Investigating the effects of high-fat diets, obesity, and exercise on cognitive function and hippocampal neurogenesis.	Understanding the impact of diet and exercise on brain health, particularly in relation to memory and cognitive function, which could inform lifestyle recommendations and interventions.	94
82	Alzheimer's, BBB, Neuroin- flammation	Investigating the relationship between Alzheimer's disease, blood-brain barrier breakdown, and neuroinflammation.	Early diagnosis of Alzheimer's disease and potential development of non-pharmacological interventions targeting blood-brain barrier integrity and neuroinflammation.	57
83	ALS, FTD, TDP-43	Neurodegenerative diseases involving TDP-43 proteinopathies and motor neuron degeneration.	Investigating the role of TDP-43, SOD1, and other genes in ALS, FTD, and related neurodegenerative diseases, and developing potential therapies such as Nusinersen.	507

Topic	Label	Summary	Application	Size
84	Telemedicine Neurology	Assessing and managing neurological symptoms and disorders during the COVID-19 pandemic through telemedicine.	Telemedicine enables remote assessment and management of fatigue, depression, anxiety, and other neurological symptoms in patients with multiple sclerosis, Parkinson's disease, and other movement disorders.	60
85	Axon Guidance	The topic focuses on axon guidance and growth cone dynamics in the nervous system, involving various guidance cues, signaling molecules, and cytoskeletal components.	Understanding axon guidance and growth cone dynamics can contribute to the development of therapies for nerve injuries and degenerative disorders.	57
86	Neural Development	Exploration of neural development and differentiation processes in the central nervous system.	Understanding the molecular mechanisms and signaling pathways involved in neural development, which can inform neurotechnology applications for neural regeneration and repair.	107
87	Axonal Regeneration	The topic focuses on axonal regeneration and nerve repair in the central and peripheral nervous systems, involving Schwann cells, myelination, and various inhibitory factors.	This neurotechnology theme is relevant for developing strategies to promote nerve regeneration and functional recovery after injuries, such as spinal cord injury, and for enhancing remyelination in degenerative conditions.	183
88	Stem Cell Therapy	Neurotechnology for the treatment of traumatic brain injury and spinal cord injury using stem cells and related processes.	Stem cell transplantation and related processes promote functional recovery, remyelination, and neurogenesis in traumatic brain injury and spinal cord injury patients.	522
89	Parkinson's Gait Analysis	Investigation of gait and freezing of gait in Parkinson's disease patients to improve mobility and reduce falls.	Assessing and improving gait characteristics in Parkinson's disease patients through rehabilitation, treadmill training, and cueing techniques.	92
90	Adult Neurogenesis	Adult neurogenesis in the dentate gyrus of the hippocampus and its role in learning and memory.	Understanding adult hippocampal neurogenesis can lead to potential interventions for enhancing cognitive functions and treating neurological disorders.	129

Topic	Label	Summary	Application	Size
91	Neurogenesis, Cell Migration	The topic focuses on the process of neurogenesis, specifically the generation and migration of various neural cell types in the brain, including oligodendrocytes, neurons, and astrocytes.	Understanding neurogenesis and neural cell migration can contribute to the development of therapies for neurodegenerative diseases and brain injuries.	437
92	Stroke Diagnosis & Treatment	Diagnosis and treatment of acute ischemic stroke using neuroimaging and reperfusion therapies.	Utilizing magnetic resonance imaging (MRI) and computed tomography angiography (CTA) for stroke diagnosis, and applying mechanical thrombectomy and intravenous thrombolysis for reperfusion treatment.	163
93	COVID-19 Neurology	Neurological manifestations and complications of COVID-19 infection.	Investigating neurological symptoms and complications in COVID-19 patients, such as encephalopathy, seizures, and Guillain-Barré syndrome, to improve diagnosis and treatment.	236
94	Multiple Sclerosis	Investigation of multiple sclerosis (MS) and its effects on the central nervous system (CNS) with a focus on demyelination, inflammation, and axonal damage.	Understanding the pathogenesis of MS and exploring potential neurotechnology interventions to mitigate demyelination and promote remyelination in the CNS.	118
95	Gut-Brain Axis	Investigating the relationship between gut microbiota and neurodegenerative disorders, particularly Parkinson's disease and Alzheimer's disease.	Understanding the role of gut microbiota in the pathogenesis of neurodegenerative disorders may lead to potential therapeutic interventions, such as probiotics or fecal microbiota transplantation.	57
96	Genetics, Neuroimaging, Psychiatry	Investigating the genetic and neurobiological factors associated with bipolar disorder, aggression, and other psychiatric conditions.	Using multimodal neuroimaging and EEGs to study the effects of genetic variations and early-life adversity on brain function and behavior.	69
97	Neuroprotection, Parkinson's, Resveratrol	Neuroprotective effects of resveratrol and other compounds in Parkinson's disease and neurodegenerative disorders.	Resveratrol and related compounds may protect dopaminergic neurons from oxidative stress and cell death, potentially improving symptoms and slowing disease progression in Parkinson's disease and other neurodegenerative disorders.	59

Topic	Label	Summary	Application	Size
98	Exercise Cognition	The topic explores the relationship between physical activity, aerobic exercise, and cognitive function, particularly in the context of aging and neuroplasticity.	This research can inform the development of exercise-based interventions to improve cognitive function, prevent cognitive decline, and promote brain health in aging populations.	103
99	Exercise Therapy	Exploring the effects of physical exercise on neuromuscular disorders, cognitive function, and depression.	Physical exercise interventions can be used to improve muscle strength, cognitive function, and alleviate depressive symptoms in patients with neuromuscular disorders and neurological injuries.	74
100	miRNA Neurodegeneration	Investigating the role of microRNAs in neurodegenerative diseases, particularly Alzheimer's disease, and their potential as biomarkers and therapeutic targets.	MicroRNAs can be used as potential biomarkers for early diagnosis of Alzheimer's disease and other neurodegenerative disorders, as well as targets for therapeutic interventions.	128
101	MS Treatment Monitoring	Multiple sclerosis treatment and monitoring using disease-modifying therapies and neuroimaging techniques.	Disease-modifying therapies (DMTs) are used to manage multiple sclerosis (MS) symptoms and progression, while neuroimaging techniques like MRI help monitor disease activity and treatment effectiveness.	160
102	Autoantibodies, Diagnosis, Immunotherapy	Investigation of autoantibodies and their role in neuromyelitis optica spectrum disorders and autoimmune encephalitis.	Detection and diagnosis of autoimmune neurological disorders, guiding targeted immunotherapies.	166
103	Neuro-degenerative Biomarkers	Detection and monitoring of neurodegenerative diseases using cerebrospinal fluid biomarkers and related methods.	Identifying and tracking the progression of diseases like Parkinson's, Alzheimer's, and dementia using cerebrospinal fluid biomarkers, α -synuclein, and other related methods.	70
104	Dementia Neuroimaging	Investigating dementia and Alzheimer's disease using neuroimaging techniques and biomarkers.	Utilizing PET scans, amyloid imaging, and biomarkers to diagnose and monitor Alzheimer's disease and other dementias.	304

Topic	Label	Summary	Application	Size
105	Cognitive Assessment	Assessment and diagnosis of cognitive impairment and neurodegenerative diseases using various methods and tools.	Identifying and differentiating between various cognitive impairments and neurodegenerative diseases such as Alzheimer's, Parkinson's, and frontotemporal dementia using tests like MMSE, MoCA, and neuroimaging techniques.	135
106	Parkinson's Management	Managing motor complications and non-motor symptoms in Parkinson's disease patients using various neurotechnology approaches.	Deep brain stimulation (STN-DBS) and dopaminergic treatments are used to alleviate motor complications and improve quality of life in Parkinson's disease patients.	58
107	HRV Mental Health	Investigating the relationship between heart rate variability (HRV) and various mental health conditions such as depression, anxiety, and stress.	Using HRV measurements and neuroimaging techniques like fMRI to assess emotional reactivity, self-regulation, and the effectiveness of psychological therapies.	66
108	Diabetes-Alzheimer's Link	Investigating the relationship between diabetes and Alzheimer's disease, and the potential neuroprotective properties of diabetes medications.	Understanding the role of insulin signaling and resistance in Alzheimer's disease, and exploring the potential use of diabetes medications like metformin and liraglutide for neuroprotection and treatment.	63
109	AD Biomarkers	Investigation of cerebrospinal fluid (CSF) biomarkers for Alzheimer's disease (AD) diagnosis and disease progression monitoring.	Utilizing CSF biomarkers such as tau, A β 42, and NfL to improve early diagnosis of Alzheimer's disease and monitor disease progression in patients with dementia and mild cognitive impairment.	191
110	Parkinson's Assessment	Assessment and management of Parkinson's disease symptoms and related disorders.	Monitoring and evaluating motor and non-motor symptoms in Parkinson's disease patients, and guiding treatment strategies.	110
111	Neuro-degenerative Disorders	Investigation of neurodegenerative disorders, particularly Parkinson's disease, and their diagnosis, symptoms, and treatment.	Utilizing neuroimaging techniques like MRI and assessing motor and non-motor symptoms to diagnose and monitor neurodegenerative disorders.	72

Topic	Label	Summary	Application	Size
112	BBB, Drug Delivery, CNS	Investigation of the blood-brain barrier (BBB) and its role in maintaining the central nervous system (CNS) homeostasis and drug delivery.	Understanding BBB permeability and dysfunction can help develop targeted drug delivery methods and improve treatment of CNS diseases.	111
113	Psychiatric Neuroimaging	Investigation of brain structures and their relationship with psychiatric disorders using neuroimaging techniques.	Identifying structural changes in the hippocampus and amygdala related to major depressive disorder, ADHD, bipolar disorder, and other psychiatric conditions, as well as evaluating the effects of treatments like electroconvulsive therapy.	138
114	Neuroprotection, Ischemia, Stroke	Investigation of neuroprotective effects and mechanisms in cerebral ischemia/reperfusion injury.	Identifying potential neuroprotective agents and understanding their mechanisms to reduce brain damage and improve recovery after ischemic stroke.	72
115	Ischemic Stroke, Neuroinflammation	Investigation of neuroinflammation and cellular responses in ischemic stroke and brain injury.	Understanding the role of inflammation, immune cells, and cellular death mechanisms in ischemic stroke and brain injury to develop potential neuroprotective strategies.	235
116	Stroke Rehabilitation	Neurotechnology for stroke rehabilitation and spinal cord injury recovery.	Assessment and improvement of motor function, sensory feedback, and proprioceptive information in stroke and spinal cord injury patients through stimulation protocols and rehabilitation strategies.	52
117	Brain-Computer Interface	Brain-computer interfaces (BCIs) enable communication and control through brain signals, often using electroencephalography (EEG) for signal processing.	BCIs are used for assisting individuals with motor disabilities, rehabilitation, and human-computer interaction, with applications such as P300 spellers and cursor control.	212
118	Microglial Activation	Investigation of microglial activation and its role in neuroinflammation and neurodegenerative diseases.	Understanding microglial activation can help develop targeted therapies for neurodegenerative diseases and improve our knowledge of the central nervous system's immune response.	340

Topic	Label	Summary	Application	Size
119	AD Immunotherapy	Immunotherapy approaches targeting Alzheimer's disease pathology.	Utilizing passive immunization and anti-A β antibodies to reduce amyloid deposits and tau pathology in Alzheimer's disease patients.	53
120	fNIRS, fMRI, Neuroimaging	Functional near-infrared spectroscopy (fNIRS) and functional magnetic resonance imaging (fMRI) are neuroimaging techniques used to study brain activity, particularly in relation to language processing, motor tasks, and hemodynamic responses.	These techniques are applied to investigate neural activity, blood flow, and oxygenation in the brain, aiding in the understanding of language comprehension, aphasia, and other cognitive processes.	110
121	Alzheimer's Neuro-inflammation	Investigating the role of microglia and astrocytes in neuroinflammation and Alzheimer's disease pathology.	Understanding the involvement of microglia and astrocytes in Alzheimer's disease may lead to potential therapeutic targets for reducing neuroinflammation and slowing disease progression.	211
122	Chronic Pain Management	Assessment and management of chronic pain using neurotechnology.	Neurotechnology can be used to assess pain intensity, severity, and related factors, as well as to provide pain relief and management through non-pharmacological interventions.	363
123	Spine Surgery	Spine surgery involving decompression, fusion, and implants for pain relief and functional improvement.	Neurotechnology applications include the use of implants in spine surgery and the use of magnetic resonance imaging for preoperative planning and postoperative assessment.	61
124	Pain Neuro-stimulation	Neurostimulation techniques for pain relief in spinal cord injury and neuropathic pain conditions.	Spinal cord stimulation (SCS) and other neurostimulation methods are used to alleviate chronic neuropathic pain and improve quality of life in patients with spinal cord injury (SCI) and other pain-related conditions.	74
125	ASD Neuroimaging	Investigating neural connectivity and brain structure in autism spectrum disorders (ASD) using neuroimaging techniques.	Identifying differences in brain regions, connectivity, and structure in individuals with ASD compared to controls, which may aid in diagnostic classification and understanding the neurobiological pathways involved in ASD.	102

Topic	Label	Summary	Application	Size
126	Bipolar Disorder Networks	Exploration of brain regions and networks involved in bipolar disorder and their potential role in cognitive and motor functions.	Identification of specific brain regions and networks for targeted neurostimulation or neuroimaging to better understand and potentially treat bipolar disorder.	93
127	Neuroimaging Analysis	Investigation of brain activity and neural dynamics using EEG, MEG, and fMRI techniques.	Analyzing motor cortex activity, sensorimotor areas, and cognitive tasks using various neuroimaging and signal processing methods.	162
128	Parkinson's Neuroprotection	Neurodegeneration and inflammation in Parkinson's disease and potential neuroprotective strategies.	Investigating neuroprotective effects of various compounds and understanding microglial activation in Parkinson's disease.	92
129	Dyslexia Neuroimaging	Investigating the neurobiological basis of developmental dyslexia and its impact on reading and language skills using neuroimaging techniques.	Utilizing functional magnetic resonance imaging (fMRI) and other neuroimaging methods to identify neural systems and brain organization involved in dyslexia, which can inform targeted interventions and improve reading outcomes.	60
130	Semantic Neuroimaging	Investigating the neural basis of semantic memory and processing using neuroimaging techniques.	Understanding the neural correlates of semantic cognition and language processing, which can inform interventions for language and cognitive disorders.	138
131	Parkinson's Neuroinflammation	Investigation of Parkinson's disease pathogenesis and neuroinflammation.	Understanding the role of α -synuclein, dopaminergic neurons, and microglial activation in Parkinson's disease to develop potential neuroprotective therapies.	65
132	Parkinson's Disease, α -synuclein, Neurodegeneration	Investigation of the role of α -synuclein in Parkinson's disease and its impact on dopaminergic neurons and mitochondrial function.	Understanding the molecular mechanisms behind Parkinson's disease could lead to the development of novel neurotechnology-based diagnostic and therapeutic approaches.	411

Topic	Label	Summary	Application	Size
133	AD Diagnosis Neuroimaging	Using machine learning and neuroimaging techniques for early diagnosis and classification of Alzheimer's disease and mild cognitive impairment.	This approach involves analyzing MRI and PET scans, extracting features, and employing classifiers like support vector machines and convolutional neural networks to differentiate between Alzheimer's disease, mild cognitive impairment, and healthy controls.	94
134	AD Neuro-imaging	Investigating hippocampal atrophy and cognitive decline in Alzheimer's disease and mild cognitive impairment using neuroimaging techniques.	Utilizing magnetic resonance imaging (MRI), voxel-based morphometry (VBM), and diffusion tensor imaging (DTI) to assess hippocampal volume, gray matter atrophy, and cognitive decline in Alzheimer's disease and mild cognitive impairment.	106
135	Research Reproducibility	Improving reproducibility and reporting in neuroscience research through better statistical practices and transparency.	Enhancing the quality and reliability of neuroscience research by addressing issues like publication bias, statistical inference, and open access.	89
136	Motor Cortex Stimulation	Non-invasive brain stimulation techniques, such as tDCS and rTMS, are used to modulate motor cortex excitability and motor function.	These techniques are applied in motor learning, stroke rehabilitation, and motor recovery by modulating cortical excitability and neuroplasticity.	211
137	Non-invasive Stimulation	Transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) are non-invasive brain stimulation techniques used for motor function recovery in stroke patients.	These techniques are applied in rehabilitation settings to improve motor outcomes, motor learning, and cortical reorganization in patients with hemiplegic cerebral palsy, chronic stroke, and other neurological injuries.	107
138	Music, Plasticity, Neuroimaging	Investigation of the effects of musical training on brain plasticity, auditory processing, and cognitive abilities using neuroimaging methods.	Understanding how musical training influences brain structure and function, which can inform interventions for cognitive and motor skill development, as well as rehabilitation strategies.	56
139	Music Neuroscience	Investigation of neural processing and perception of musical rhythm and its relation to social bonding and language processing.	Utilizing electroencephalogram and functional magnetic resonance imaging to study rhythmic movements, synchronization, and neural correlates of music processing.	56

Topic	Label	Summary	Application	Size
140	Face Recognition	Investigation of face recognition and processing in the human brain using neuroimaging and electrophysiological techniques.	Understanding the neural mechanisms underlying face recognition and perception, which can inform the development of neuroprosthetics for individuals with prosopagnosia or other face processing impairments.	127
141	Oxytocin, Social Cognition	Investigation of oxytocin's role in social cognition, behavior, and its potential applications in psychiatric disorders.	Intranasal oxytocin administration may be used to modulate social cognition, behavior, and potentially treat psychiatric disorders such as autism and social anxiety.	104
142	Alzheimer's Neuroprotection	Investigating the role of oxidative stress, A β toxicity, and neuroinflammation in Alzheimer's disease and potential neuroprotective strategies.	Understanding the mechanisms of Alzheimer's disease and exploring potential neuroprotective interventions, such as antioxidants and anti-inflammatory agents.	90
143	Alzheimer's Pathogenesis	Investigation of Alzheimer's disease pathogenesis, focusing on amyloid-beta and tau protein accumulation, and their impact on cognitive decline and memory loss.	Development of neuroimaging techniques and potential non-pharmacological interventions targeting amyloid-beta and tau protein accumulation in Alzheimer's disease.	615
144	Neural Oscillations	Investigation of neural oscillations and synchronization using various neuroimaging techniques and analysis methods.	Understanding brain activity patterns, functional states, and large-scale networks in relation to cognitive tasks and resting states.	66
145	Pharmacological Treatments	Pharmacological treatments for various mental disorders.	This topic focuses on the use of various medications to treat mental disorders such as schizophrenia, bipolar disorder, and major depressive disorder.	134
146	Schizophrenia Neuroimaging	Investigating brain structure and function in schizophrenia and related disorders using neuroimaging techniques.	Identifying structural brain abnormalities and understanding cognitive reserve in schizophrenia, autism, and bipolar disorder through magnetic resonance imaging (MRI) and other imaging methods.	75

Topic	Label	Summary	Application	Size
147	Working Memory, Executive Functions, Neurofeedback	Investigation of working memory and executive functions in relation to neuropsychological disorders and cognitive abilities.	Assessing and improving working memory capacity and executive functioning through neurofeedback and cognitive training, with potential applications in schizophrenia, ADHD, and Parkinson's disease.	117
148	VTA Dopamine Circuitry	Investigation of the role of VTA dopaminergic neurons and their interactions with other neurotransmitter systems in the regulation of reward, pain, and aversion, using optogenetics and other neurotechnologies.	Understanding the neural circuits involved in reward, pain, and aversion can help develop targeted treatments for drug addiction, chronic pain, and other neurological disorders.	132
149	Placebo Analgesia Neuroimaging	Investigation of placebo analgesia and pain perception using neuroimaging techniques.	Understanding the neural mechanisms of placebo analgesia and pain perception can help develop non-pharmacological interventions for chronic pain management.	176
150	Cerebral Palsy Neuro-technology	Investigating neural circuits and behavioral responses in cerebral palsy patients to improve motor function and rehabilitation.	Understanding the neural basis of motor function and behavioral responses in cerebral palsy patients can lead to the development of targeted neurotechnology interventions for rehabilitation and improved quality of life.	57
151	Neuro-transmitter Interactions	Investigation of the interactions between dopamine, opioids, and other neurotransmitter systems in the context of pain, addiction, and schizophrenia.	Understanding the mechanisms underlying pain relief, addiction, and schizophrenia to develop targeted non-pharmacological interventions.	78
152	Opioid Pain Management	Opioid use and management in chronic pain treatment.	Monitoring and regulating opioid use in chronic pain patients, and exploring alternative neurotechnology-based pain management methods.	61
153	Schizophrenia, Bipolar, Neurobiology	Investigating the genetic and neurobiological factors contributing to schizophrenia and bipolar disorder, focusing on the prefrontal cortex and hippocampus.	Understanding the pathophysiology of schizophrenia and bipolar disorder may lead to improved diagnostic tools and targeted treatments, potentially involving neurostimulation techniques.	178

Topic	Label	Summary	Application	Size
154	fMRI Cognitive Research	Investigating the relationship between working memory, cognitive control, and functional connectivity in the prefrontal cortex using functional magnetic resonance imaging (fMRI) and its implications for various conditions such as schizophrenia, autism, and aging.	This neurotechnology can be applied to better understand cognitive development, cognitive aging, and the neural basis of executive functions, potentially informing interventions for conditions like schizophrenia, autism, and age-related cognitive decline.	85
155	Brain Connectivity Imaging	Investigating brain structure and connectivity changes in various neurological conditions and aging using diffusion tensor imaging (DTI) and magnetic resonance imaging (MRI).	Identifying structural and functional connectivity differences in conditions like schizophrenia, Alzheimer's disease, and autism, as well as understanding normal brain development and aging.	468
156	Speech Processing Neurotechnology	Investigation of speech processing, comprehension, and production in the human auditory cortex using neuroimaging techniques.	Understanding and improving speech recognition, comprehension, and production in various conditions, including language disorders and schizophrenia.	191
157	Functional Connectivity	Investigating functional connectivity and organization of brain networks in aging and neuropsychiatric disorders using resting-state fMRI.	Understanding the changes in functional connectivity patterns and network organization in the brain during aging and in neuropsychiatric disorders, which can inform diagnosis and treatment strategies.	58
158	Memory Neuroimaging	The topic focuses on the neural basis and neuroimaging of episodic and autobiographical memory, involving brain regions such as the hippocampus, medial temporal lobes, and default mode network.	Neuroimaging techniques like functional MRI and PET scans are used to study the neural correlates of memory retrieval, self-referential processing, and the brain's default mode network.	58
159	Meditation Neuroimaging	Investigating the effects of meditation and mindfulness practices on various mental disorders and emotional regulation through neuroimaging techniques.	Using functional magnetic resonance imaging (fMRI) to study the impact of meditation and mindfulness on brain regions like the amygdala, prefrontal cortex, and insula, which are involved in emotional processing, decision making, and interoception.	250

Topic	Label	Summary	Application	Size
160	VWFA, Language, Neuroimaging	Investigation of the visual word form area (VWFA) and its role in language acquisition, development, and processing using neuroimaging techniques.	Understanding the neural basis of reading and language processing, and identifying potential interventions for language impairments.	59
161	Language Neurotechnology	Investigation of language comprehension and processing using neuroimaging and event-related potentials (ERPs) techniques.	Understanding neural correlates of language processing, including syntax, semantics, and speech perception, to inform language acquisition and development research.	178
162	Taste Neuroscience	Investigating the neural mechanisms underlying obesity, taste perception, and eating disorders using neuroimaging techniques.	Understanding the brain's response to food stimuli and taste can help develop interventions for eating disorders and obesity.	151
163	Addiction Neuroscience	Investigation of neural mechanisms and pathways involved in drug addiction and seeking behaviors, focusing on the nucleus accumbens and related brain regions.	Understanding the neural basis of addiction can inform the development of targeted neurotechnology interventions for addiction treatment and relapse prevention.	209
164	Addiction Neurotechnology	Investigating the neural mechanisms of addiction and craving, and the potential use of neurotechnology interventions such as rTMS and DBS for treatment.	Using rTMS and DBS to target specific brain regions involved in addiction and craving, potentially aiding in smoking cessation and reducing drug dependence.	91
165	Cannabinoid Neuro-transmission	The topic focuses on the interactions between cannabinoids, such as THC and CBD, and various neurotransmitter systems, including serotonin and dopamine, in the context of drug abuse, dependence, and psychosis.	Understanding these interactions can help in developing targeted interventions for substance abuse disorders and psychosis, as well as exploring the potential therapeutic uses of cannabinoids.	56
166	Schizophrenia, Substance Use, Genetics	Investigation of genetic and neurochemical factors associated with schizophrenia, substance use, and related disorders.	Identification of genetic variations and neurochemical imbalances that contribute to schizophrenia and substance use disorders, potentially informing the development of targeted neurotechnology interventions.	68

Topic	Label	Summary	Application	Size
167	Mood Disorders, Addiction	Investigation of the effects of various substances on mood disorders, addiction, and psychiatric disorders.	Understanding the neurobiological mechanisms and potential treatment options for mood disorders, addiction, and psychiatric disorders.	195
168	Fear Conditioning Extinction	Investigation of fear conditioning and extinction processes in the amygdala and related brain regions.	Understanding the neural mechanisms of fear conditioning and extinction can inform the development of treatments for anxiety disorders and post-traumatic stress disorder.	134
169	Cognition, Fear, Disorders	Investigating cognitive and neuropsychological deficits in various mental disorders and their relation to fear conditioning and extinction.	Understanding cognitive impairments and fear-related processes in mental disorders can inform the development of targeted neurotechnology interventions, such as deep brain stimulation or transcranial magnetic stimulation.	102
170	MRI Segmentation	The topic involves the use of various segmentation methods, including manual and automatic, to analyze brain structures such as the hippocampus, thalamus, and amygdala using MRI data.	These segmentation techniques are applied in the study of neurological diseases like Alzheimer's and multiple sclerosis, as well as in brain development and aging research.	66
171	Cognitive Neuroscience	Exploration of cognitive processes and mental states using computational modeling and brain imaging techniques.	Understanding human cognition, behavior, and social interactions through computational models and neuroimaging methods.	60
172	Diffusion MRI Tractography	Diffusion MRI tractography is a neuroimaging technique that maps white matter tracts and brain connectivity using diffusion tensor imaging (DTI) and advanced algorithms.	This technique is used to visualize and study white matter anatomy, fiber orientation, and brain connectivity, providing valuable insights into neurological disorders and brain function.	341
173	Working Memory Oscillations	Investigation of brain oscillations and neural activity during working memory tasks and their relation to memory encoding and cognitive functions.	Using EEG and magnetoencephalography to study oscillatory activity in the brain during working memory tasks, potentially leading to improved understanding and interventions for cognitive disorders like schizophrenia.	141

Topic	Label	Summary	Application	Size
174	BDNF, Mood Disorders, Metabolic Syndrome	Investigation of the relationship between BDNF, mood disorders, and metabolic syndrome.	Understanding the role of BDNF in mood disorders and metabolic syndrome may lead to improved diagnosis and treatment strategies for psychiatric disorders.	91
175	Maternal Stress Effects	Investigation of the effects of maternal care, maternal separation, and stress on the development of anxiety, emotionality, and stress responses in animal models.	Understanding the impact of early-life stress on brain development and behavior; potentially informing interventions for mental health disorders.	113
176	Animal Model Behavior	Investigating behavioral phenotypes and cognitive functions in animal models of autism and schizophrenia using various behavioral tests and tasks.	Understanding the neurobehavioral development, cognitive deficits, and anxiety-like behaviors in animal models to inform potential neurotechnology interventions for autism and schizophrenia.	51
177	Inflammation, Cytokines, Depression	Investigation of the relationship between inflammation, cytokines, and depressive disorders.	Understanding the role of inflammation and cytokines in depression and schizophrenia may lead to novel neurotechnology-based treatments targeting these pathways.	154
178	EEG Locomotion Analysis	Investigating the relationship between EEG signals and walking patterns to understand motor control and locomotion.	This can be applied to improve brain-computer interfaces (BCIs) for gait rehabilitation and assistive technologies for individuals with mobility impairments.	56
179	Arcuate Fasciculus Connectivity	Investigation of the arcuate fasciculus and its role in functional connectivity, language networks, and cognitive functions using neuroimaging techniques such as fMRI and DTI.	Understanding the connectivity patterns and functional interactions in the brain related to language, cognition, and disorders such as schizophrenia and autism.	70
180	Functional Connectivity	Exploration of functional connectivity in the brain using neuroimaging techniques such as fMRI and ICA to analyze resting-state networks and their relationship with various cognitive and neurological conditions.	This approach helps in understanding the organization and connectivity patterns of brain networks, which can be useful in studying and diagnosing conditions like schizophrenia and other neurological disorders.	549

Topic	Label	Summary	Application	Size
181	Emotion Regulation Neuroimaging	Investigating emotion regulation strategies and their neural correlates, focusing on amygdala and prefrontal cortex activity.	Utilizing neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), to study the neural mechanisms underlying emotion regulation and its potential implications for mental health disorders.	74
182	Visual Working Memory	Investigation of visual working memory and its neural activity in the visual cortex, focusing on memory load, attention, and information processing.	Understanding visual working memory can lead to the development of neurotechnology applications for memory enhancement and attention modulation.	64
183	PTSD, Interventions, Comorbidities	Investigating PTSD and its symptoms, comorbidities, and potential interventions.	Understanding the neural substrates of PTSD and exploring non-pharmacological interventions such as exposure therapy and behavioral interventions.	64
184	Decision Neuroscience	Investigating the neural mechanisms underlying delay discounting and decision-making in relation to impulsivity and risk-taking behaviors.	Utilizing functional magnetic resonance imaging (fMRI) and tasks like the Iowa Gambling Task (IGT) to study brain activation patterns in regions such as the prefrontal cortex, insula, and striatum, which are involved in decision-making and reward processing.	66
185	Neural Synchrony	Neural synchrony in cognitive processes and social interactions during learning and problem-solving.	Investigating neural synchronization during cooperative learning and social engagement using techniques like fNIRS and event-related potentials (ERP).	51
186	Social Neuroscience	Investigation of the neural basis of theory of mind, mental states, and social cognition, focusing on brain regions such as the amygdala, medial prefrontal cortex, and cortical midline structures.	Understanding the neural correlates of theory of mind can improve social interaction, cognitive development, and mental health by informing the design of targeted interventions and therapies.	155

Topic	Label	Summary	Application	Size
187	Functional Connectivity	Investigating functional connectivity in various mental disorders using resting-state functional magnetic resonance imaging.	Identifying abnormal connectivity patterns in mental disorders such as MDD, OCD, and ASD, which can potentially inform early intervention strategies and treatment approaches.	140
188	ADHD, ASD, Neuro-technology	Neurotechnology applications for ADHD and ASD diagnosis and treatment.	Neurofeedback, functional connectivity, and functional magnetic resonance imaging (fMRI) are used to diagnose and treat ADHD and ASD.	171
189	OFC, Dopamine, Reward	Investigation of the role of orbitofrontal cortex (OFC) and dopamine neurons in reward prediction, learning, and decision-making processes.	Understanding the neural mechanisms behind reward prediction and decision-making can help develop treatments for conditions like schizophrenia and improve behavioral flexibility.	89
190	Adolescent BPD	Investigating the relationship between adolescent development, emotion regulation, and borderline personality disorder (BPD) in the context of bullying and social support.	Utilizing neuroimaging techniques and psychological interventions to understand and improve emotion regulation and well-being in adolescents with BPD.	114
191	Visual-Motor Interaction	Investigation of the interaction between visual perception, attention, and motor learning using neuroimaging and stimulation techniques.	Enhancing motor learning and skill acquisition through targeted stimulation and modulation of visual and motor cortical areas.	214
192	BDNF Biomarker	Investigating the role of brain-derived neurotrophic factor (BDNF) in psychiatric disorders and its potential as a biomarker.	Assessing BDNF levels in serum or plasma to aid in the diagnosis and treatment monitoring of depression, schizophrenia, and bipolar disorder.	54
193	Psychiatric GWAS	Investigating genetic factors and molecular pathways associated with psychiatric disorders using genome-wide association studies (GWAS).	Identifying susceptibility genes and loci for psychiatric disorders, which can inform the development of targeted neurotechnology interventions.	247
194	Genetic Epilepsy	Genetic factors and mutations in epilepsy and related neurodevelopmental disorders.	Utilizing whole-exome sequencing and electroencephalography (EEG) to identify genetic mutations and monitor brain activity in epilepsy patients.	106

Topic	Label	Summary	Application	Size
195	Genetics, Neurodevelopment, ASD	Investigation of genetic factors and mutations in neurodevelopmental disorders such as autism spectrum disorders and schizophrenia.	Identification of specific genes and mutations associated with neurodevelopmental disorders, aiding in diagnosis and potential targeted therapies.	144
196	Muscle Synergies	Investigation of muscle synergies and their role in postural control, motor tasks, and human locomotion.	Understanding muscle activation patterns and motor control can improve neuroprosthetic devices and rehabilitation strategies for balance and locomotion.	72
197	fMRI, Empathy, Morality	Investigating the neural basis of empathy, moral judgment, and social cognition using functional magnetic resonance imaging (fMRI).	Understanding the neural mechanisms underlying empathy, moral judgment, and social cognition in various populations, including ASD, schizophrenia, and psychopathy, which can inform the development of targeted interventions.	380
198	Motor Learning, Adaptation, LFPs	Investigation of motor learning and adaptation in the motor system using neural activity and local field potentials.	Understanding motor control and improving motor performance through the analysis of neural activity and local field potentials in the motor cortex.	151
199	Facial Expression Recognition	Investigating the neural basis of facial expression recognition and its role in social interactions.	Improving facial expression recognition in clinical populations and enhancing social learning through neurostimulation techniques like rTMS.	99
200	Amygdala fMRI	Investigating amygdala activation and responses to emotional facial expressions using functional magnetic resonance imaging (fMRI).	This neurotechnology can be applied to study emotional processing, social cognition, and empathy, as well as to understand disorders like autism and schizophrenia.	59
201	Pandemic Mental Health	Mental health issues during the COVID-19 pandemic, including anxiety, depression, and PTSD.	Neurotechnology applications could involve monitoring mental health status and providing targeted interventions, such as neurofeedback or non-invasive brain stimulation.	266

Topic	Label	Summary	Application	Size
202	Estrogen, Memory, Neuroprotection	The topic focuses on the role of estrogen and other sex hormones in memory, cognition, and neuroprotection, particularly in the hippocampus.	Understanding the effects of estrogen and sex hormones on memory and cognition can help develop targeted neuroprotective strategies and treatments for cognitive decline and neurodegenerative diseases.	81
203	Hormonal Regulation	Investigation of the role of kisspeptin and GnRH neurons in the hypothalamus and their influence on sex differences, fertility, and hormonal regulation.	Understanding the neural mechanisms behind hormonal regulation and reproduction, potentially leading to treatments for fertility issues and hormonal imbalances.	59
204	Social Neuroendocrinology	Investigation of the role of hormones and neuropeptides in social behavior and cognition.	Understanding the neural circuits and mechanisms behind social behavior, aggression, and memory, potentially informing treatments for autism and mood disorders.	95
205	Stress, Depression, Neurobiology	Investigation of the effects of chronic stress and depression on the brain, focusing on the HPA axis, hippocampus, and prefrontal cortex.	Understanding the neurobiological mechanisms underlying stress and depression can inform the development of targeted neurotechnology interventions, such as deep brain stimulation or transcranial magnetic stimulation.	541
206	Rubber Hand Illusion	Investigating the rubber hand illusion and its effects on body ownership, peripersonal space, and multisensory integration.	Understanding the neural mechanisms behind the rubber hand illusion can help improve prosthetic hand design and enhance body perception in patients with amputations or sensory impairments.	100
207	Cortisol Measurement	Assessing cortisol levels and stress responses using salivary cortisol measurements and Trier Social Stress Test (TSST).	This neurotechnology is used to study the hypothalamic-pituitary-adrenal (HPA) axis, stress responses, and their relation to various psychological and psychiatric disorders such as PTSD, MDD, and childhood trauma.	112

Topic	Label	Summary	Application	Size
208	Mental Disorder Treatment	Assessment and treatment of various mental disorders, including depression and anxiety.	Neurotechnology applications include non-invasive brain stimulation techniques for treating mental disorders and monitoring brain activity to assess treatment efficacy.	133
209	Visual Cortex Processing	Investigation of the primary visual cortex (V1) and its role in orientation selectivity, adaptation, and neural responses in the visual system.	Understanding the mechanisms behind visual processing and improving visual prosthetics or neuroimaging technologies.	50
210	Neuroimaging Psychiatry	Neuroimaging techniques applied to various mental disorders and their symptoms.	Investigating the neural correlates of mental disorders such as OCD, eating disorders, and schizophrenia, and assessing the effectiveness of treatments like CBT.	84
211	Mental Disorders	Exploration of various mental disorders and their impact on behavior, emotions, and well-being.	Assessment and diagnosis of mental disorders, informing treatment planning and interventions.	90
212	Stress, Aging, Epigenetics	Investigating the relationship between stress, PTSD, and biological aging through telomere length and DNA methylation.	Understanding the impact of stress on cellular aging and brain structures, potentially leading to targeted interventions for stress-related disorders.	82
213	Trauma, PTSD, Neuroimaging	Investigating the impact of childhood maltreatment and trauma on brain structure and function, and its relation to PTSD and other psychopathologies.	Utilizing neuroimaging techniques to identify changes in amygdala and hippocampal volumes, and to understand the neural mechanisms underlying fear conditioning and extinction in individuals with PTSD.	75
214	Reward Processing	Investigation of neural mechanisms underlying reward processing, decision making, and reinforcement learning using functional magnetic resonance imaging (fMRI) and event-related brain potentials (ERPs).	Understanding the neural basis of reward processing and decision making can inform the development of neurotechnology for treating disorders related to reward dysfunction and improving cognitive control.	215
215	fMRI Object Recognition	Investigation of object recognition and category membership in the ventral visual pathway using functional magnetic resonance imaging (fMRI).	Understanding object processing and category structure in the human brain, and identifying the brain regions involved in visual perception and categorization.	61

Topic	Label	Summary	Application	Size
216	Visual Attention Research	Investigation of visual attention and perception through eye movements, neural activity, and visual processing in the visual cortex.	Using functional magnetic resonance imaging (fMRI) and eye tracking to study the neural mechanisms of visual attention, object recognition, and multisensory integration in the visual system.	849
217	Memory Neuroimaging	Investigating memory processes and neural mechanisms in the brain using neuroimaging techniques.	Understanding memory encoding, retrieval, and consolidation in the medial temporal lobe and prefrontal cortex using functional magnetic resonance imaging (fMRI).	180
218	Cognitive Control	Investigation of response inhibition and cognitive control processes in the prefrontal cortex and anterior cingulate cortex using neuroimaging and psychophysiological techniques.	Understanding the neural mechanisms underlying inhibitory control, error processing, and executive processes, which can inform the development of interventions for cognitive disorders and improve cognitive performance.	247

Note: Only research topics in shaded rows were analyzed further as the remaining topics did not yield any potentially Neurotechnology-related content, according to the GPT-4.

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Table 8. Topics identified in the filtered patent corpus

Topic	Summary	Application	Label	Count
1	Multimodal neuromodulation techniques for deep or superficial brain stimulation to treat neurological and psychiatric conditions.	These methods impact multiple points in neural circuits to produce Long-Term Potentiation (LTP) or Long-Term Depression (LTD) and can be used to treat conditions such as obsession, compulsion, anxiety, depression, Parkinson's disease, and other movement disorders.	Multimodal Neuromodu- lation	535
2	Monitoring and evaluating driver behavior and preferences using biometric information and vehicle data.	Creating personalized driver models for autonomous vehicles and providing real-time safe driving evaluation based on vehicle-mounted intelligent units.	Driver Behavior Analysis	527
3	Speech recognition technology using hierarchical word clustering and acoustic feature parameters.	Improves speech recognition accuracy and processing rate by clustering words and analyzing acoustic features of input utterances.	Speech Recognition	458
4	Natural language processing using neural networks for word vector generation and language model training.	Enhancing semantic information learning, increasing convergence speed of word vectors, and improving training effects in natural language processing systems.	NLP Neural Networks	410
5	Image-based object detection and recognition using convolutional neural networks.	Improving object detection and recognition in images for intelligent information processing and computer vision applications.	Image Object Detection	376
6	Neuromorphic processing devices using resistive memory cells and artificial synapses with spike-timing dependent plasticity for event-driven learning and reward modulation.	These devices can be used for creating artificial neural networks that mimic biological neural networks, enabling efficient and adaptive computation in neuromorphic computers.	Neuromorphic Computing	366
7	Automatic medical recommendation and image enhancement using convolutional neural networks for various medical imaging modalities.	Improving medical image analysis and diagnosis by enhancing image quality, segmenting structures, and providing medical recommendations based on machine learning classifiers.	Medical Image Analysis	353

Topic	Summary	Application	Label	Count
8	Photosensitive resin compositions for liquid crystal display elements	These compositions are used for forming spacers, interlayer organic insulating films, and color filters in liquid crystal display devices.	LCD Photosensitive Resin	314
9	3D face image generation and recognition using convolution neural networks and cross-modal space mapping.	Generating 3D face images from single images and improving facial recognition speed and accuracy across different modalities.	3D Face Recognition	262
10	Optical signal detection and characterization in low-coherence interferometry and optical devices.	Determining information on the structure and location of interfaces in objects, measuring optical electric field waveforms, and characterizing optical devices.	Optical Interferometry	247
11	Neurotechnology for limb rehabilitation using augmented reality, brain-computer interfaces, and virtual reality.	The technology aids in gait and limb rehabilitation by guiding patients through exercises in virtual environments, providing feedback, and evaluating progress using electroencephalogram signals and motion sensors.	Limb Rehabilitation	234
12	Fluorescence-based detection and imaging techniques for biological samples.	These techniques involve using fluorescent probes and dyes for labeling target cells, measuring oxygen concentration, and generating super-resolution biological microscopy images.	Fluorescence Imaging	230
13	Neurotechnology related to music, audio data, and singing voice synthesis.	Potential applications include using neural interfaces to control music creation, performance, and synthesis, as well as analyzing and evaluating user's mental or physical states through musical interactions.	Music Neurotechnology	203
14	Real-time analysis of brain wave data for detecting and predicting seizures and brain dysfunction.	The neurotechnology applications involve real-time analysis of electroencephalogram (EEG) or electrocorticogram (ECoG) signals to detect or predict seizures and brain dysfunction, and provide relevant information for diagnosis or treatment.	Seizure Prediction	190

Topic	Summary	Application	Label	Count
15	Stereoscopic display devices for enhanced 3D vision without the need for special glasses.	These devices provide a more natural and comfortable 3D viewing experience, with applications in entertainment, gaming, and medical imaging.	Stereoscopic Displays	179
16	Pain treatment using voltage-gated sodium channel inhibitors, GLP-1 receptor agonists, and delta opioid agonists.	These compounds and compositions target central nervous system receptors and channels to alleviate various types of pain, including neuropathic, chronic, and inflammatory pain.	Pain Management	174
17	Neurotechnology is not directly involved in wagering and gaming systems.	None	Not applicable	169
18	Emotion recognition and expression in robots and devices using neural networks, fuzzy inference, and bio-signal sensing.	These technologies can be used in interactive multimedia, advertisement, and personalized user experiences, as well as in emotion-guided robotic systems and emotion estimation devices.	Emotion Recognition	167
19	Identification and diagnosis of neuropsychiatric disorders using genetic markers.	Utilizing specific gene markers and mutations for diagnosing, monitoring, and treating neuropsychiatric disorders such as autism, bipolar disorder, ADHD, and schizophrenia.	Genetic Diagnostics	159
20	Treatment and prevention of neurodegenerative diseases using compounds and inhibitors.	Inhibition of astrogliosis after cerebral ischemia injury, and treatment of neurodegenerative diseases such as Alzheimer's and Parkinson's disease.	Neuro-degenerative Treatment	154
21	Antibodies targeting specific proteins and their applications in disease treatment.	These antibodies can be used for treating diseases related to misfolded or aggregated proteins, such as neurodegenerative disorders.	Targeted Antibodies	149
22	Robotic control systems using sensor data and natural intelligence for autonomous behavior and multitasking.	These systems enable robots to autonomously select and execute motions, learn from sensor data and control data, and perform multitasking through distributed control systems.	Autonomous Robotics	149

Topic	Summary	Application	Label	Count
23	Brain-computer interfaces for controlling devices and improving classification performance.	These interfaces enable users to control external devices, such as robot arms, using brain signals and maintain classification performance even after long periods of non-use.	Brain-Computer Interface	146
24	Analyzing social networks and their influence on users.	Enhancing social values through network-based systems and analyzing relationship quality metrics in digital social networks.	Social Network Analysis	142
25	Wireless communication systems and feedback mechanisms	Techniques for reducing overhead in wireless communication systems, such as HARQ feedback and transmission power control.	Wireless Communication	138
26	Identification of biomarkers in cerebrospinal fluid and blood-derived exosomes for diagnosing and assessing neurodegenerative diseases such as Alzheimer's disease.	These methods involve obtaining biological samples from subjects and measuring specific biomarkers to diagnose, assess risk, monitor progression, and evaluate therapy efficacy for neurological diseases.	Neuro-degenerative Biomarkers	137
27	Neurotechnology for tinnitus treatment and hearing enhancement using electrical stimulation and sound enrichment.	Estimating uncomfortable loudness levels using electroencephalogram signals, and providing tinnitus relief and hearing enhancement through synchronized electrical stimulation and sound enrichment based on ambient sound environment classification.	Tinnitus Neurotechnology	130
28	Augmented reality processing and display systems using captured images and scene environment information.	These systems capture images with augmented reality environment information, determine display positions based on real positions, and display related information in the reality display area.	Augmented Reality	127
29	Neurotechnology in gaming and interactive educational tools.	Cognitive enhancement and personality development through interactive games, puzzles, and educational programs.	Cognitive Gaming	127

Topic	Summary	Application	Label	Count
30	Monitoring and improving sleep quality using personalized sleep classifiers and sleep guidance systems.	Creating personalized sleep classifiers based on biosignals and high-accuracy sleep studies, and guiding sleepers through optimal sleep patterns using sensory stimuli.	Sleep Optimization	117
31	Neuroimaging techniques for analyzing brain connectivity and white matter tracts using diffusion magnetic resonance imaging (dMRI) and atlas-based methods.	These techniques enable the creation of individualized brain atlases, detection of white matter hyperintensity regions, and automatic extraction of white matter tracts in patients, even with edema or brain perturbations.	Brain Connectivity Imaging	115
32	Gene transfer techniques and transgenic mouse models for neurological diseases.	Gene transfer techniques for treating and preventing brain nervous system diseases, and transgenic mouse models for dementia and Alzheimer's disease research.	Gene Transfer, Transgenic Models	106
33	Neural network-based learning and interaction system for cyborgs or androids with human-like senses.	Enhancing human-machine interaction and communication through reinforcement learning, natural language processing, and sensory input integration.	Cyborg AI Interaction	103
34	Eye tracking using infrared light and gaze detection in wearable displays.	Tracking gaze position in target space and detecting gaze errors in eye tracking devices.	Eye Tracking	96
35	Exoskeletons with electromyographic control and adjustable stiffness joints assist human movement and support the upper and lower limbs.	These exoskeletons can be used for rehabilitation, mobility assistance, and support for individuals with physical disabilities or injuries.	Assistive Exoskeletons	92
36	Assessing cognitive function using walking motion and multi-touch devices.	Evaluating cognitive functions related to ADHD and other disorders by analyzing walking motion data and engaging individuals in cognitive exercises using multi-touch devices.	Cognitive Assessment	86
37	Assessment of visual system characteristics using various testing apparatus and methods.	Testing visual acuity, refractive characteristics, ocular muscle balance, visual field mapping, dark adaptation, and depth perception in human subjects.	Visual System Assessment	84

Topic	Summary	Application	Label	Count
38	Robots with personality traits that interact and communicate with users and other robots.	These robots can adapt their personalities based on user information and preferences, improving user experience and engagement.	Personality Robots	83
39	Cross-modal neural input processing for image description and named entity identification in social media short texts.	Enhancing image description accuracy and information expression, and supplementing social media short text data with visual object information for named entity identification.	Cross-modal Neural Processing	83
40	Voice-responsive toys and dolls that simulate communication with children through eye movement and speech recognition.	Interactive toys and dolls that respond to children's voices by moving their eyes or changing their mode, enhancing engagement and simulating communication.	Voice-responsive toys	82
41	Efficient learning method for multi-agent deep reinforcement learning with action selection neural network training and weakly supervised reinforcement learning.	Training neural networks for multi-agent systems in decentralized control with communication or centralized training with decentralized execution environments.	Multi-Agent Reinforcement Learning	72
42	Optical coherence tomography (OCT) devices and methods for imaging and analyzing samples using interference patterns and fixed pattern noise.	These OCT devices and methods can be used for real-time, three-dimensional imaging and motion analysis of biological tissues, potentially aiding in medical diagnostics and treatment planning.	Optical Coherence Tomography	67
43	Magnetic resonance imaging (MRI) techniques for improved spatial and temporal resolutions, artifact reduction, and motion tracking.	These MRI techniques can be used for acquiring high-resolution images with fewer artifacts, tracking subject motion, and correcting phase errors caused by alternating gradient magnetic field polarities.	Advanced MRI Techniques	63
44	Differentiation of glial progenitor cells, astrocytes, and oligodendrocytes from embryonic stem cells.	Screening of toxic materials related to cells and assessing toxicity, induction of neuronal fate in neural stem cells or neural progenitor cells, and isolation of neuronal progenitor cells, oligodendrocyte progenitor cells, or neural stem cells from embryonic stem cells.	Stem Cell Differentiation	62

Topic	Summary	Application	Label	Count
45	Neurotechnology for speech and auditory processing, including speech analysis for health monitoring, controlling hearing prostheses, and electronic speech aids for hypokinetic dysarthria.	Speech analysis can be used to assess a speaker's physiological health, while speech processors can control hearing prostheses and electronic speech aids can improve speech intelligibility for individuals with hypokinetic dysarthria.	Speech Neurotechnology	62
46	Neurotechnology not applicable	N/A	Not applicable	60
47	Methods and tools for teaching reading and spelling using mnemonics, connectable blocks, and wheels.	Enhancing reading and spelling skills through the use of mnemonics, connectable blocks with reading indicia, and combination wheels for encoding and decoding words.	Reading Education	57
48	Image encoding and decoding techniques	These techniques involve processing and compressing image data for efficient storage and transmission, but do not have direct neurotechnology applications.	Image Compression	55
49	Neural network-based analysis of electrocardiogram signals for heart disease diagnosis and fetal heart rate prediction.	Utilizes artificial neural networks and deep learning algorithms to process electrocardiogram data for diagnosing heart diseases and predicting fetal heart rates.	ECG Neural Analysis	52
50	Magnetic resonance imaging techniques for evaluating performance, signal processing, and reducing motion artifacts.	Phantom for evaluating MRSI performance, signal processing method for intra voxel incoherent motion imaging, and multi-frame MR tomography system for reducing motion artifacts.	MRI Techniques	50
51	Chimeric proteins involving the extracellular domain of colony stimulating factor 1 receptor (CSF1R) and their use in treating diseases, such as immunotherapies for cancer and/or inflammatory diseases.	These chimeric proteins can be used in immunotherapies for cancer and inflammatory diseases by targeting the CSF1R pathway.	CSF1R Chimeric Proteins	48

Topic	Summary	Application	Label	Count
52	Non-invasive methods and devices for assessing cerebral blood flow and hemodynamic state of the brain using near-infrared spectroscopy and other optical techniques.	These methods and devices can be used for monitoring blood-brain barrier dynamics, determining the levels of various analytes in the brain or blood, and assessing intracranial pressure and cerebral blood flow.	Cerebral Monitoring	47
53	Personalized audio encoding and decoding based on psychoacoustic models and user's auditory features.	Improves audio quality experience by encoding and decoding audio data according to user's auditory feature information and psychoacoustic model parameters.	Psychoacoustic Audio Encoding	43
54	Gesture recognition using touch and non-touch systems, multichannel electromyographic signals, and vision-based methods for human-machine interaction.	Gesture recognition methods can be used in various applications, such as human-machine interaction, tracking and detection of motion, and conveying messages through predefined gestures.	Gesture Recognition	43
55	Monitoring and analyzing muscle fatigue and exercise effects using physiological parameters.	Measuring muscle fatigue after exercise and prescribing exercise programs based on heart rate and maximum oxygen intake.	Exercise Analysis	38
56	Wireless communication synchronization signal block designs	Facilitates channel estimation and demodulation in 5G New Radio networks by providing various synchronization signal block designs.	5G Synchronization	38
57	Assessing and monitoring brain performance profiles and diagnosing neuropsychiatric disorders using computer-based methods and brain activity data.	Identifying changes in an individual's brain performance profile, diagnosing attention deficit hyperactivity disorder (ADHD) using peripheral skin temperature data, and computing a brain function index for diagnosing mental disorders at the individual level.	Brain Performance Assessment	36

Topic	Summary	Application	Label	Count
58	High-throughput molecular docking for assessing binding ligands and pharmaceutical compounds, and determining mutable ligand-GPCR binding at single amino acid resolution.	Screening combinatorial libraries to identify binding ligands, optimizing ligand-target molecule complex formation, and modifying binding affinity and stability of GPCR-ligand complexes for diagnostic purposes or pharmacological intervention.	Molecular Docking, GPCR Binding	32
59	Advanced X-ray imaging systems and methods for improved contrast and multi-energy imaging.	These technologies are used in medical imaging for better visualization of internal structures and enhanced contrast in X-ray computed tomography (CT) scans.	X-ray Imaging	32
60	Facial expression recognition using attention mechanisms and neural networks.	Improving accuracy in facial expression recognition by embedding hybrid attention modules into convolutional and recurrent neural networks.	Facial Expression Recognition	32
61	Biomarker-based methods for predicting and treating cardiovascular complications in heart failure and diabetes patients.	These methods involve measuring specific biomarkers (e.g., IGFBP2, pro-neurotensin 1-117, cardiac hormones) in blood, plasma, or urine samples to predict the risk of cardiovascular events and guide treatment decisions.	Cardiovascular Biomarkers	29
62	Echo cancellation and signal processing in communication systems	Improving signal quality and reducing interference in communication systems by removing unwanted signals and echoes	Signal Cancellation	28
63	Radioligands for PET imaging of LRRK2 and Tau aggregates in the brain.	Visualizing LRRK2 and Tau aggregates in the brain using Positron Emission Tomography (PET) for diagnosing disorders like Alzheimer's disease and other tauopathies.	PET Radioligands	27
64	Hair dyeing with specific chemical compounds	Oxidative dyeing of keratin fibers, especially human hair, using specific chemical compounds and dyeing agents.	Hair Dyeing	27

Topic	Summary	Application	Label	Count
65	Treatment of Parkinson's disease using levodopa and related compounds.	Methods for treating Parkinson's disease by administering levodopa and related compounds, often in combination with other drugs, to provide rapid relief of motor fluctuations.	Parkinson's Treatment	22
66	Inhibition of synaptic vesicle protein 2A (SV2A) for treating cognitive impairment	Using SV2A inhibitors, such as levetiracetam, seletacetam, and brivaracetam, to improve cognitive function in subjects with age-related cognitive impairment or at risk thereof.	SV2A Inhibition	22
67	Hybrid stethoscope combining sound and visual waveform for enhanced diagnosis.	Physicians can concurrently hear and see an analog waveform of internal body sounds, facilitating better analysis and diagnosis of disorders.	Hybrid Stethoscope	21

Note Shaded rows indicated topics containing particularly apparent neurotechnology applications (indication by GPT-4) Topics

Source: authors' own compilation on data from European Patent Office's Worldwide Patent Statistical Database (PATSTAT) (2000-2020)

Table 9. Examples of patent application titles of neurotechnology topics (2 examples per topic)

Topic	Application ID	Application title
Face Recognition	21446619	Discrimination Transforms Applied To Frequency Domain Derived Feature Vectors
Face Recognition	406207904	Facial Image Quality Assessment
Visual Cortex Processing	40863239	Apparatus and Method for Color Registration
Visual Cortex Processing	456790520	Wavelength Encoded Multi-Beam Optical Coherence Tomography
Visual Working Memory	365751228	Image Registration
Visual Working Memory	521651369	Transmissive Head Mounted Display Apparatus, Support System, Display Control Method, and Computer Program
Visual Attention Research	376243774	Recognition and Pose Determination of 3D Objects in Multimodal Scenes
Visual Attention Research	520585325	Methods and Apparatus for Projecting Augmented Reality Enhancements to Real Objects In Response to User Gestures Detected in a Real Environment
Muscle Synergies	333903699	Electric Power Steering Device
Muscle Synergies	38410027	Impedance Type Reaction Capacity Measuring Device
Automated Driving Neuroergonomics	379842382	Driver State Determination Device
Automated Driving Neuroergonomics	494271274	Planning Feedback Based Decision Improvement System for Autonomous Driving Vehicle
Cochlear Implants	51622188	Interoral Electrolarynx
Cochlear Implants	48139460	Method of Using Dermatomal Somatosensory Evoked Potentials In Real-Time for Surgical and Clinical Management
Visual-Motor Interaction	445920741	Systems and Methods for Providing Haptic Feedback for Remote Interactions
Visual-Motor Interaction	49126358	Electronic Mouse
Speech Processing Neurotechnology	50626179	Statistical Acoustic Processing Method and Apparatus for Speech Recognition Using a Toned Phoneme System
Speech Processing Neurotechnology	46708032	Universal Guide Track
Rubber Hand Illusion	52726706	Interface to Convert Mental States and Facial Expressions to Application Input

Topic	Application ID	Application title
Rubber Hand Illusion	47090312	Validator for Electrocardial Data Processing System
Language Neurotechnology	442144997	Term Probabilistic Model for Co-Occurrence Scores
Language Neurotechnology	439759656	Oxymoron Collecting Device and Computer Program for the Same
Music, Plasticity, Neuroimaging	519564291	Information Processing Method and Information Processor
Music, Plasticity, Neuroimaging	516852524	Systems and Methods for Designing Haptics Using Speech Commands
Neural Synchrony	544447881	Method and System for Providing Interaction Service Using Smart Toy
Neural Synchrony	322134866	Calculation Game and Program
VWFA, Language, Neuroimaging	53610287	Word Disambiguation Apparatus and Methods
VWFA, Language, Neuroimaging	405807131	Autism Diagnosis Support Method and System, and Autism Diagnosis Support Device
Bilingualism Neuroimaging	23149077	Synthesising Speech From Text
Bilingualism Neuroimaging	32881777	Voice Recognition Interactive Processing Method and Processor Therefor
fMRI Object Recognition	30071116	Light Source
fMRI Object Recognition	533620060	Image Recognition Method and Image Recognition Device Based on Feature Extraction
Deep Learning Neuroimaging	494015704	Medical Image Segmentation
Deep Learning Neuroimaging	549161581	Apparatus and Method for Medical Diagnostic
Cognitive Neuroscience	470924795	An Education System Using Virtual Robots
Cognitive Neuroscience	497186526	Generating Simulated Sensor Data for Training and Validation of Detection Models
Reward Processing	528992672	Skillful Casino Multi-Level Games and Regulated Gaming Machines In Which Progressively Higher Game Levels Enable Progressively Higher Returns to Player (Rtp)
Reward Processing	53725831	System and Method for Wagering Based on Financial Market Indicators
Fear Conditioning Extinction	23029326	Speech Coding
Fear Conditioning Extinction	51263864	Inhibitors of Catalytic Antibodies

Topic	Application ID	Application title
Microelectrode Arrays	315787359	A Flexible, Multi-Channel Microelectrode for Recording Laboratory Animal EEG and Method for Recording Laboratory Animal EEG Using the Same
Microelectrode Arrays	52994197	Multi-Channel Implantable Neural Stimulator
Motor Learning, Adaptation, LFPs	444033938	Servodrive with Controllable Action Force
Motor Learning, Adaptation, LFPs	496827772	Method and Arrangement for Generating Control Commands for an Autonomous Road Vehicle
Epilepsy Neurotechnology	52332465	Active Derivative of Valproic Acid for the Treatment of Neurological and Psychotic Disorders and a Method for their Preparation
Epilepsy Neurotechnology	29960263	Thienylazole Compound and Thienotriazolodiazepine Compound
Visual Cortex Plasticity	574443342	Method for Detecting White Matter Lesions Based on Medical Image
Visual Cortex Plasticity	50870779	Two-Photon Laser Microscopy
Semantic Neuroimaging	376243774	Recognition and Pose Determination of 3D Objects in Multimodal Scenes
Semantic Neuroimaging	534694757	Semantic Matching Method and Device, Equipment and Storage Medium
Optogenetics	58054110	Biological Sample Observation Method
Optogenetics	328681898	Fluorescence Observation Apparatus
Memory Neuroimaging	23016187	Devices for Use in Neural Processing
Memory Neuroimaging	504453753	Specific Binding Reagent for Detecting Qualitative Difference of 4 Repeat Tau, Test Method Using the Same, Test Kit, and Screening Method for Medicine
Cognitive Control	478960791	Big Telematics Data Constructing System
Cognitive Control	39320116	Method for Controlling Head Positioning, Device for Controlling Head Positioning, and Disk Device
Neocortical Circuits	548227232	Integrate-and-Fire Neuron Circuit Using Single-Gated Feedback Field-Effect Transistor
Neocortical Circuits	492986484	Robot Arm, Robot Control Device, and Robot System
Numerical Cognition	510731087	A Computer-Implemented Method, an Apparatus and a Computer Program Product for Assessing Performance of a Subject in a Cognitive Function Test
Numerical Cognition	442144997	Term Probabilistic Model for Co-Occurrence Scores

Topic	Application ID	Application title
Neuropathic Pain Mechanisms	24812119	New Analgesic Octa: hydro-Isoquinoline Derivs – Are Selective Delta Opioid Receptor Agonists, Useful in Treatment of Pain
Neuropathic Pain Mechanisms	17605891	Indol Derivatives Useful for the Treatment of Migraine, Composition and Utilization
Neural Circuit Visualization	365212590	Neuron-Specific Retrograde Transport Vector
Neural Circuit Visualization	38292639	Analysis Apparatus, Analysis Method, Program and Recording Medium
OFC, Dopamine, Reward	34301206	Agent Learning Device
OFC, Dopamine, Reward	27994050	Echo Control System
Pain Neurostimulation	407627915	Pharmacological Stimulation to Facilitate and Restore Standing and Walking Functions in Spinal Cord Disorders
Pain Neurostimulation	470850730	Method and Apparatus for Detection of Intrinsic Depolarization Following High Energy Cardiac Electrical Stimulation
Memory Neuroimaging	34925463	Game Development Control Method Reflecting Character of Player, Video Game Device and Record Medium
Memory Neuroimaging	34925480	Method for Diagnosing Affinity with Game Character, Video Game Device and Record Medium
VTA Dopamine Circuitry	34811375	Indole-3-Carboxamide Derivative
VTA Dopamine Circuitry	23094778	Heteroaromatic Compounds
Music Neuroscience	513583600	Trill Modeling Method, Device, Computer Equipment and Storage Medium
Music Neuroscience	489411082	Multi-Sound-Source Audio Processing Device Capable of Helping Sleep
Parkinson's Gait Analysis	19075782	Treadmill and User Weight Lightening Device Combining Device for Patient, Has Fixed/Movable Support Rods Provided from Front to Back, Where Maximum Height of Device Parts Does Not Exceed Horizontal Plane Passing Via Lower End of Sternum
Parkinson's Gait Analysis	517939228	Rehabilitation Robot Training System for Monitoring and Restraining Compensatory Movement of Hemiplegia Upper Limb
Exercise Therapy	49760457	Method for Enhanced Performance Training
Exercise Therapy	486244625	Method and Apparatus of Assessing Cardiopulmonary Fitness

Topic	Application ID	Application title
Dyslexia Neuroimaging	48362437	Computer Implemented Method of Analyzing Recognition Results Between a User and an Interactive Application Utilizing Inferred Values Instead of Transcribed Speech
Dyslexia Neuroimaging	48494188	Multidirectional Sound Reproduction
Chronic Pain Management	21454546	Triazole Compounds Useful in Therapy
Chronic Pain Management	51767472	Substituted Benzodiazepin-10-Ones and Method of Use
Facial Expression Recognition	58075899	Laugh Detector and System and Method for Tracking an Emotional Response to a Media Presentation
Facial Expression Recognition	56768141	Facial Animation Using Motion Capture Data
Epilepsy Surgery Neuroimaging	413885720	Method and System of Detecting Seizures
Epilepsy Surgery Neuroimaging	20560593	New Aminomethyl Benzo(A) Quinolizidine Derivatives Having Alpha 2 Adrenergic Receptor Antagonist Activity
fMRI, Empathy, Morality	53844335	Probability Game with Insured Winning
fMRI, Empathy, Morality	2570280	Psychometric Instruments and Methods for Mood Analysis Psychoeducation and Therapy
Bipolar Disorder Networks	19065540	New N-(Piperidinyl)(Phenyl)Methyl Benzamide Derivatives are Glycine Transport Inhibitors, Useful for the Treatment of e.g. Dementia-Associated Behavioral Problems, Psychoses, Anxiety, Depression and Alcohol Abuse
Bipolar Disorder Networks	27564567	Derivative of 2-Azetidinone-4-Carboxylic Acid
MS Treatment Monitoring	331406458	Methods and Means for Diagnosing Vasculitis
MS Treatment Monitoring	52636692	Monoclonal Antibodies Against Autoimmune Rna Proteins
Stroke Diagnosis & Treatment	247810	List Mode-Based Respiratory and Cardiac Gating in Positron Emission Tomography
Stroke Diagnosis & Treatment	547982605	Dual Layer Icad Device
Epilepsy Detection	492347358	Automatic Electrocardiogram Analysis Method and Device Based on Artificial Intelligence Self-Learning
Epilepsy Detection	492180823	Anomaly Detection Using Magnetic Resonance Fingerprinting
Diffusion MRI Tractography	471594475	Generalized Spherical Deconvolution in Diffusion Magnetic Resonance Imaging
Diffusion MRI Tractography	23067271	Techniques(N1)

Topic	Application ID	Application title
Motor Cortex Stimulation	470599588	Compounds for Treatment of Intractable Epilepsy and Doors Syndrome
Motor Cortex Stimulation	330282781	N-(4-[6-Fluoro-3,4-Dihydroisoquinolin-2(1h)-yl]-2,6-Dimethylphenyl)-3,3-Dimethylbutanamide as Potassium Channel Modulators
Purkinje Synaptic Plasticity	21314742	Therapeutic Agents
Purkinje Synaptic Plasticity	23278999	Dopamine D-1 Receptor Agonist Compounds
fMRI Cognitive Research	491366378	Anti-Fraud Recognition Method, Storage Medium and Server With Safe Computer
fMRI Cognitive Research	16691876	Echo Canceling Device for Data Transmission Over Two-Wire Line
fMRI, epilepsy, anesthesia	47869969	Method and Apparatus for Determining the Cerebral State of a Patient with Fast Response
fMRI, epilepsy, anesthesia	51429798	Electroconvulsive Therapy Method Using Ictal EEG Data as an Indicator of ECT Seizure Adequacy
Social Neuroscience	352310744	Evolution of a User Interface Based on Learned Idiosyncrasies and Collected Data of a User
Social Neuroscience	524550638	Misinformation Detection in Online Content
Amygdala fMRI	479959211	Novel Polypeptides
Amygdala fMRI	313584162	Humanized Anti Cxcr4 Antibodies for the Treatment of Cancer
Arcuate Fasciculus Connectivity	496317723	Neuromorphic Circuits for Storing and Generating Connectivity Information
Arcuate Fasciculus Connectivity	53659144	Inter-Subject Coherence in Dt-Mri
Cerebral Palsy Neurotechnology	487659147	System, Method and Program for Generating Hand Finger Movement Practice Menu
Cerebral Palsy Neurotechnology	298710684	System and Method for Taking Responsive Action to Human Biosignals
Stroke Rehabilitation	16402240	Rehabilitation System for Neurological Disorders
Stroke Rehabilitation	52263195	Automatic Detection and Correction of Body Organ Motion and Particularly Cardiac Motion in Nuclear Medicine Studies
Sleep Memory Consolidation	536340601	Sleep Detection Method and Device and Sleep Aiding Equipment and Method
Sleep Memory Consolidation	549389222	Automatic Sleep Staging Establishing Method and Application Thereof

Topic	Application ID	Application title
STN DBS	2508012	Method and Apparatus For Measurement of Evoked Neural Response
STN DBS	52219589	Method of Positioning Electrodes for Central Nervous System Monitoring
Sleep Neurotechnology	563329596	Using Personalized Physiological Parameters for Sleep/Wake Detection
Sleep Neurotechnology	456114294	Sleep State Determination Device, Sleep State Determination Method, and Sleep Management System
Working Memory, Executive Functions, Neurofeedback	54280946	3,3'-Disubstituted-1,3-Dihydro-2h-Pyrrolo[2,3-B] Heterocyclic-2-One Useful In The Treatment of Cognitive Disorders of Man
Working Memory, Executive Functions, Neurofeedback	38617112	Interface Device, Interface Method, and Control Training Device Using the Interface Device
ASD Neuroimaging	274180865	Differential Diagnosis of Neuropsychiatric Conditions
ASD Neuroimaging	28311634	Automatic Brain Activity Judging Device
AD Diagnosis Neuroimaging	574397490	Method for Predicting Disease Based on Medical Image
AD Diagnosis Neuroimaging	487057494	Tomographic Data Analysis
Functional Connectivity	413562121	Tracking Interactions with Forwarded Links by Evaluating Similarity of Forwarded Links and Evaluating a Chain of Forwarding
Functional Connectivity	267466353	Analyzing Transactional Data
Addiction Neuroscience	49694373	Benzisothiazole and Benzisoxazole Piperazine Derivatives
Addiction Neuroscience	22856058	Cinnoline Compounds
Decision Neuroscience	50668547	Real-Time Interactive Wagering on Event Outcomes
Decision Neuroscience	409426722	Gaming System, Gaming Device, and Method Providing One or More Alternative Wager Propositions If a Credit Balance is Less Than a Designated Wager Amount
Working Memory Oscillations	527346542	Image Display Method, Device and System
Working Memory Oscillations	484474934	Energy-Efficient Time-Multiplexed Neurosynaptic Core for Implementing Neural Networks Spanning Power – and Area-Efficiency
Olfactory Dysfunction	48069392	Drugs for Prophylaxis or Mitigation of Taxane-Induced Neurotoxicity

Topic	Application ID	Application title
Olfactory Dysfunction	51244715	1-Benzyl-2-Aminomethyl Imidazole Derivatives
Non-invasive Stimulation	46605564	System and Method of Prediction of Response to Neurological Treatment Using the Electroencephalogram
Non-invasive Stimulation	449271254	Rehabilitation System and Control Method of Rehabilitation System
Parkinson's Management	49181020	Compositions and Methods for Treating Cns Disorders
Parkinson's Management	50559598	Treatment of Movement Disorders by Administration of Mirtazapine
TBI Neurotechnology	21347372	Method for Typing a Tse Strain
TBI Neurotechnology	444295469	Methods
Neuroprotection, Ischemia, Stroke	48544339	Pyridinium Compounds
Neuroprotection, Ischemia, Stroke	422743816	Method for Selectively Inhibiting Acat1 in the Treatment of Neurodegenerative Diseases
Cognition, Fear, Disorders	23006551	Therapeutic Agents
Cognition, Fear, Disorders	35054367	Monoclonal Antibody Against Human Thymidylc Acid Synthase and Hybridoma Producing the Same Antibody
GABA, Memory, Plasticity	456935108	Tdp-43-Binding Polypeptides Useful for the Treatment of Neurodegenerative Diseases
GABA, Memory, Plasticity	528118369	Neuromorphic Device Using Crossbar Memory
AD Biomarkers	126453	Method for the Detection of Amyloid-Beta Oligomers in Body Fluids
AD Biomarkers	472776033	Method for Monitoring Clinical and Pathological Alzheimer's Disease Using Amyloid Beta Concentration in Plasma
EEG Locomotion Analysis	54342855	Monitor and Method for Acquiring and Processing Electrical Signals Relating to Bodily Functions
EEG Locomotion Analysis	273847680	System and Method for Neurometric Analysis
fNIRS, fMRI, Neuroimaging	53266162	Assessing Blood Brain Barrier Dynamics or Identifying or Measuring Selected Substances or Toxins in a Subject by Analyzing Raman Spectrum Signals of Selected Regions in the Eye
fNIRS, fMRI, Neuroimaging	475146310	Apparatus and Method for Measuring the Blood Oxygen Saturation in a Subject's Tissue

Topic	Application ID	Application title
Brain Connectivity Imaging	55444193	Method for Diagnosing a Pervasive Developmental Disorder
Brain Connectivity Imaging	320719250	Median Plane Deciding Device and Magnetic Resonance Imaging Equipment
Brain-Computer Interface	328472478	Monitoring Neurological Electrical Signals to Detect The Onset of a Neurological Episode
Brain-Computer Interface	315675643	Apparatus and Method for Alzheimer's Disease Diagnosis Using EEG (Electroencephalogram) Analysis
Gut-Brain Axis	23189520	Detection of Variations in Human Histamine H2 Receptors
Gut-Brain Axis	322552225	Method for Diagnosis
Placebo Analgesia Neuroimaging	50678947	Compositions Containing Dipeptidyl Peptidase IV and Tyrosinase or Phenylalaninase for Reducing Opioid-Related Symptoms
Placebo Analgesia Neuroimaging	334198535	Acquiring Nerve Activity from Carotid Body and/or Sinus
Epigenetics, Memory, Neurology	458564429	Methods of Diagnosing and Treatment of Alzheimer's Disease
Epigenetics, Memory, Neurology	4317287	Diagnosis for Malignant Hyperthermia
Neurodegenerative Biomarkers	323962461	Dipeptide Mimetics of NGF and BDNF Neurotrophins
Neurodegenerative Biomarkers	21343847	Polypeptides and their Uses
Adult Neurogenesis	531592725	- Weighing Device Based On Cross-Point Capacitor and Neural Network Using the Same
Adult Neurogenesis	23144568	Neural Cell Lines
Stem Cell Therapy	25475123	Method of Inducing Differentiation of Mesoblast Stem Cells or ES Cells Into Nerve System Cells
Stem Cell Therapy	47276827	Fibroblast Growth Factor 13
Huntington's Disease	378264607	Diagnostic Mirna Markers for Alzheimer
Huntington's Disease	16411736	Reversible Sirnaa-Based Silencing of Mutated and Endogenous Wild-Type Huntingtin Gene and Its Application for the Treatment of Huntington's Disease
Functional Connectivity	445754788	Evaluation Device and Evaluation Method
Functional Connectivity	353098287	Topology-Preserving Roi Remapping Method Between Medical Images
MRI Segmentation	544115633	Visualization of Subimage Classifications

Topic	Application ID	Application title
MRI Segmentation	548414467	Ct Method and Apparatus for Cortical Neurodegeneration Prediction in Alzheimer's Disease Using CT Images
AD Neuroimaging	53849978	Automated Detection of Alzheimer's Disease by Statistical Analysis with Positron Emission Tomography Images
AD Neuroimaging	508230678	Image System and Image Method Applied to Brain Image
Taste Neuroscience	49263653	Method for the Stimulation of Appetite in Patients
Taste Neuroscience	21515004	Novel Compounds and their Effects on Feeding Behaviour
Dementia Neuroimaging	49736087	Methods for Aiding in the Diagnosis of Alzheimer's Disease by Measuring Amyloid – Beta Peptide (X- \rightarrow /=41)
Dementia Neuroimaging	15729478	Detection of Advanced Glycation Endproducts in a Cerebrospinal Fluid Sample
ADHD, ASD, Neurotechnology	23097877	Therapeutic Agents
ADHD, ASD, Neurotechnology	23098819	Therapeutic Agents
Schizophrenia Neuroimaging	20172595	Pyridazine Derivative Having a Psychotropic Action, Method for its Preparation and the Medicaments Containing It
Schizophrenia Neuroimaging	51271222	Method of Treating Therapy-Resistant Schizophrenia with Amperozide [N-Ethyl-4-[4',4'-Bis(P-Fluorophenyl)Butyl]-1-Piperazine-Carboxamide
Neuroimaging Psychiatry	54048695	Air Sampler for Pathogens and Psychrometrics
Neuroimaging Psychiatry	4676817	Autoimmunity to Angiotensin at1 Receptors in Schizophrenia
Cognitive Assessment	53599262	Detection of Alzheimer's Disease and Other Diseases Using a Photoaffinity Labeling Method
Cognitive Assessment	380827269	Infrared Analysis of Peripheral Blood Fractions Obtained to Indicate Cognitive Development Associated with Alzheimer's Disease
Neural Oscillations	318758342	Method for Simplifying Acoustic Model Analysis through Applying Audio Frame Frequency Spectrum Flatness and Device Thereof
Neural Oscillations	419845806	Method and System to Calculate Qeeg
Addiction Neurotechnology	38694875	Therapeutic Agent for Drug Dependence

Topic	Application ID	Application title
Addiction Neurotechnology	22915478	Indolophenanthridines
Emotion Regulation Neuroimaging	49887789	Arylthiazolylimidazoles
Emotion Regulation Neuroimaging	23194227	Novel Compounds
Functional Connectivity	552312259	Method and System for Remotely Monitoring the Psychological State of an Application User Based on Average User Interaction Data
Functional Connectivity	475536923	Electronic Device Capable of Preventing Addition, and Addiction Preventive Management System and Method

Table 10. Proposed baseline IPC-based taxonomy of neurotechnology-related patents

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61B 3/00	A61B0003000000	Apparatus for testing the eyes; Instruments for examining the eyes (eye inspection using ultrasonic, sonic or infrasonic waves A61B0008100000)		
A61B 3/10	A61B0003000000	Apparatus for testing the eyes; Instruments for examining the eyes (eye inspection using ultrasonic, sonic or infrasonic waves A61B0008100000)	A61B0003100000	Objective types, i.e. instruments for examining the eyes independent of the patients perceptions or reactions
A61B 5/145	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005145000	Measuring characteristics of blood in vivo, e.g. gas concentration, pH-value (measuring of blood pressure or blood flow A61B0005020000; non-radiation detecting or locating of foreign bodies in blood A61B0005060000)
A61B 5/18	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005180000	For vehicle drivers
A61B 5/04	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005040000	Measuring bioelectric signals of the body or parts thereof

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61B 5/03	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005030000	Measuring fluid pressure within the body other than blood pressure, e.g. cerebral pressure
A61B 5/0484	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005048400	using evoked response
A61B 5/024	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005024000	Measuring pulse rate or heart rate (A61B0005020500, A61B0005021000 take precedence)
A61B 5/1455	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005145500	using optical sensors, e.g. spectral photometrical oximeters
A61B 5/01	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005010000	Measuring temperature of body parts (clinical thermometers G01K0005220000; thermometers for special purposes G01K0013000000)
A61B 5/08	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005080000	Measuring devices for evaluating the respiratory organs (A61B0005020500 takes precedence)

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61B 5/0488	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005048800	Electromyography
A61B 5/0476	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005047600	Electroencephalography
A61B 5/026	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005026000	Measuring blood flow
A61B 5/22	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005220000	Ergometry; Measuring muscular strength or the force of a muscular blow
A61B 5/103	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005103000	Measuring devices for testing the shape, pattern, size or movement of the body or parts thereof, for diagnostic purposes (A61B0005080000 takes precedence;measuring instruments specially adapted for dentistry A61C0019040000)

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61B 5/0205	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005020500	Simultaneously evaluating both cardiovascular conditions and different types of body conditions, e.g. heart and respiratory condition
A61B 5/0478	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005047800	Electrodes specially adapted therefor
A61B 5/11	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005110000	Measuring movement of the entire body or parts thereof, e.g. head or hand tremor or mobility of a limb (for measuring pulse A61B0005020000)
A61B 5/05	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005050000	Measuring for diagnosis by means of electric currents or magnetic fields (A61B0005020000, A61B0005040000, A61B0005110000 take precedence)
A61B 5/02	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005020000	Measuring pulse, heart rate, blood pressure or blood flow; Combined pulse/heart-rate/blood pressure determination; Evaluating a cardiovascular condition not otherwise provided for, e.g. using combinations of techniques provided for in this group with electrocardiography; Heart catheters for measuring blood pressure

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61B 5/16	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005160000	Devices for psychotechnics (using teaching or educational appliances G09B0001000000-G09B0007000000); Testing reaction times
A61B 5/00	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons		
A61B 5/055	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005055000	involving electronic [EMR] or nuclear [NMR] magnetic resonance, e.g. magnetic resonance imaging
A61B 5/12	A61B0005000000	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	A61B0005120000	Audiometry
A61B 6/03	A61B0006000000	Apparatus for radiation diagnosis, e.g. combined with radiation therapy equipment (instruments measuring radiation intensity for application in the field of nuclear medicine, e.g. in vivo counting, G01T0001161000;apparatus for taking X-ray photographs G03B0042020000)	A61B0006030000	Computerised tomographs (echo-tomography A61B0008140000)

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61B 6/00	A61B0006000000	Apparatus for radiation diagnosis, e.g. combined with radiation therapy equipment (instruments measuring radiation intensity for application in the field of nuclear medicine, e.g. in vivo counting, G01T0001161000;apparatus for taking X-ray photographs G03B0042020000)		
A61B 6/04	A61B0006000000	Apparatus for radiation diagnosis, e.g. combined with radiation therapy equipment (instruments measuring radiation intensity for application in the field of nuclear medicine, e.g. in vivo counting, G01T0001161000;apparatus for taking X-ray photographs G03B0042020000)	A61B0006040000	Positioning of patients; Tilttable beds or the like (operating tables A61G0013000000; operating chairs A61G0015000000)
A61B 8/00	A61B0008000000	Diagnosis using ultrasonic, sonic or infrasonic waves		
A61B 8/08	A61B0008000000	Diagnosis using ultrasonic, sonic or infrasonic waves	A61B0008080000	Detecting organic movements or changes, e.g. tumours, cysts, swellings (A61B0008020000- A61B0008060000 take precedence)
A61B 10/00	A61B0010000000	Other methods or instruments for diagnosis, e.g. for vaccination diagnosis; Sex determination; Ovulation-period determination; Throat striking implements		
A61B 34/30	A61B0034000000	Computer-aided surgery; Manipulators or robots specially adapted for use in surgery	A61B0034300000	Surgical robots

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61F 2/70	A61F0002000000	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000; dental prostheses A61C0013000000; materials for prostheses A61L0027000000; artificial hearts A61M0001100000; artificial kidneys A61M0001140000]	A61F0002700000	Electrical
A61F 2/20	A61F0002000000	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000; dental prostheses A61C0013000000; materials for prostheses A61L0027000000; artificial hearts A61M0001100000; artificial kidneys A61M0001140000]	A61F0002200000	Larynxes; Tracheae combined with larynxes or for use therewith (tracheae, bronchi per se A61F0002040000)

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61F 2/72	A61F0002000000	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000;dental prostheses A61C0013000000;materials for prostheses A61L0027000000;artificial hearts A61M0001100000;artificial kidneys A61M0001140000)	A61F0002720000	Bioelectric control, e.g. myoelectric
A61F 2/68	A61F0002000000	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000;dental prostheses A61C0013000000;materials for prostheses A61L0027000000;artificial hearts A61M0001100000;artificial kidneys A61M0001140000)	A61F0002680000	Operating or control means

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61F 5/01	A61F0005000000	Orthopaedic methods or devices for non-surgical treatment of bones or joints (surgical instruments or methods for treatment of bones or joints, devices specially adapted therefor A61B0017560000); Nursing devices (bandages, dressings or absorbent pads A61F0013000000)	A61F0005010000	Orthopaedic devices, e.g. long-term immobilising or pressure directing devices for treating broken or deformed bones such as splints, casts or braces
A61F 5/58	A61F0005000000	Orthopaedic methods or devices for non-surgical treatment of bones or joints (surgical instruments or methods for treatment of bones or joints, devices specially adapted therefor A61B0017560000); Nursing devices (bandages, dressings or absorbent pads A61F0013000000)	A61F0005580000	Apparatus for correcting stammering or stuttering
A61F 11/00	A61F0011000000	Methods or devices for treatment of the ears, e.g. surgical; Protective devices for the ears, carried on the body or in the hand (headwear, e.g. caps or helmets, with means for protecting the ears A42B0001060000, A42B0003160000)		
A61F 11/04	A61F0011000000	Methods or devices for treatment of the ears, e.g. surgical; Protective devices for the ears, carried on the body or in the hand (headwear, e.g. caps or helmets, with means for protecting the ears A42B0001060000, A42B0003160000)	A61F0011040000	Devices or methods enabling ear patients to replace direct auditory perception by another kind of perception

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61H 1/02	A61H0001000000	Apparatus for passive exercising (A61H0005000000 takes precedence); Vibrating apparatus; Chiropractic devices, e.g. body impacting devices, external devices for briefly extending or aligning unbroken bones	A61H0001020000	Stretching or bending apparatus for exercising
A61H 3/00	A61H0003000000	Appliances for aiding patients or disabled persons to walk about (apparatus for helping babies to walk A47D0013040000)		
A61K 47/10	A61K0047000000	Medicinal preparations characterised by the non-active ingredients used, e.g. carriers or inert additives; Targeting or modifying agents chemically bound to the active ingredient	A61K0047100000	Alcohols; Phenols; Salts thereof, e.g. glycerol; Polyethylene glycols [PEG]; Poloxamers; PEG/POE alkyl ethers
A61K 51/00	A61K0051000000	Preparations containing radioactive substances for use in therapy or testing in vivo		
A61K 51/04	A61K0051000000	Preparations containing radioactive substances for use in therapy or testing in vivo	A61K0051040000	Organic compounds
A61K 101/02	A61K0101000000	Radioactive non-metals	A61K0101020000	Halogens
A61K 101/00	A61K0101000000	Radioactive non-metals		
A61N 1/00	A61N0001000000	Electrotherapy; Circuits therefor (A61N0002000000 takes precedence;electrically conductive preparations for use in therapy or testing in vivoA61K0050000000)		
A61N 1/372	A61N0001000000	Electrotherapy; Circuits therefor (A61N0002000000 takes precedence;electrically conductive preparations for use in therapy or testing in vivoA61K0050000000)	A61N0001372000	Arrangements in connection with the implantation of stimulators

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A61N 1/04	A61N0001000000	Electrotherapy; Circuits therefor (A61N0002000000 takes precedence;electrically conductive preparations for use in therapy or testing in vivoA61K0050000000)	A61N0001040000	Electrodes
A61N 1/36	A61N0001000000	Electrotherapy; Circuits therefor (A61N0002000000 takes precedence;electrically conductive preparations for use in therapy or testing in vivoA61K0050000000)	A61N0001360000	for stimulation, e.g. heart pace-makers
A61N 1/05	A61N0001000000	Electrotherapy; Circuits therefor (A61N0002000000 takes precedence;electrically conductive preparations for use in therapy or testing in vivoA61K0050000000)	A61N0001050000	for implantation or insertion into the body, e.g. heart electrode (A61N0001060000 takes precedence)
A61N 2/00	A61N0002000000	Magnetotherapy		
A61N 2/02	A61N0002000000	Magnetotherapy	A61N0002020000	using magnetic fields produced by coils, including single turn loops or electromagnets (A61N0002120000 takes precedence)
A61N 7/00	A61N0007000000	Ultrasound therapy (lithotripsy A61B0017220000, A61B0017225000;massage using supersonic vibration A61H0023000000)		
A61P 25/28	A61P0025000000	Drugs for disorders of the nervous system	A61P0025280000	for treating neurodegenerative disorders of the central nervous system, e.g. nootropic agents, cognition enhancers, drugs for treating Alzheimer's disease or other forms of dementia

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
A63B 21/00	A63B0021000000	Exercising apparatus for developing or strengthening the muscles or joints of the body by working against a counterforce, with or without measuring devices (electric or electronic controls therefor A63B0024000000)		
A63B 24/00	A63B0024000000	Electric or electronic controls for exercising apparatus of groups A63B0001000000- A63B0023000000		
B25J 9/16	B25J0009000000	Programme-controlled manipulators	B25J0009160000	Programme controls (total factory control, i.e. centrally controlling a plurality of machines, G05B0019418000)
B25J 9/00	B25J0009000000	Programme-controlled manipulators		
B25J 13/08	B25J0013000000	Controls for manipulators (programme controls B25J0009160000)	B25J0013080000	by means of sensing devices, e.g. viewing or touching devices
C07B 59/00	C07B0059000000	Introduction of isotopes of elements into organic compounds		
C07D 471/14	C07D0471000000	Heterocyclic compounds containing nitrogen atoms as the only ring hetero atoms in the condensed system, at least one ring being a six-membered ring with one nitrogen atom, not provided for by groups C07D0451000000- C07D0463000000	C07D0471140000	Ortho-condensed systems
C07F 13/00	C07F0013000000	Compounds containing elements of Groups 7 or 17 of the Periodic System		
C12M 1/34	C12M0001000000	Apparatus for enzymology or microbiology	C12M0001340000	Measuring or testing with condition measuring or sensing means, e.g. colony counters

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
C12N 15/09	C12N0015000000	Mutation or genetic engineering; DNA or RNA concerning genetic engineering, vectors, e.g. plasmids, or their isolation, preparation or purification; Use of hosts therefor (mutants or genetically engineered microorganisms C12N0001000000, C12N0005000000, C12N0007000000;new plants A01H;plant reproduction by tissue culture techniques A01H0004000000;new animals A01K0067000000;use of medicinal preparations containing genetic material which is inserted into cells of the living body to treat genetic diseases, gene therapy A61K0048000000;peptides in general C07K)	C12N0015090000	Recombinant DNA-technology
C12Q 1/00	C12Q0001000000	Measuring or testing processes involving enzymes, nucleic acids or microorganisms (measuring or testing apparatus with condition measuring or sensing means, e.g. colony counters, C12M0001340000); Compositions therefor; Processes of preparing such compositions		

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
C12Q 1/68	C12Q0001000000	Measuring or testing processes involving enzymes, nucleic acids or microorganisms (measuring or testing apparatus with condition measuring or sensing means, e.g. colony counters, C12M0001340000); Compositions therefor; Processes of preparing such compositions	C12Q0001680000	involving nucleic acids
C12Q 1/02	C12Q0001000000	Measuring or testing processes involving enzymes, nucleic acids or microorganisms (measuring or testing apparatus with condition measuring or sensing means, e.g. colony counters, C12M0001340000); Compositions therefor; Processes of preparing such compositions	C12Q0001020000	involving viable microorganisms
G01B 9/02	G01B0009000000	Instruments as specified in the subgroups and characterised by the use of optical measuring means (arrangements for measuring particular parameters G01B0011000000)	G01B0009020000	Interferometers
G01B 11/02	G01B0011000000	Measuring arrangements characterised by the use of optical means (instruments of the types covered by group G01B0009000000per seG01B0009000000)	G01B0011020000	for measuring length, width, or thickness (G01B0011080000 takes precedence)
G01J 3/26	G01J0003000000	Spectrometry; Spectrophotometry; Monochromators; Measuring colours	G01J0003260000	using multiple reflection, e.g. Fabry-Perot interferometer, variable interference filter

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G01J 3/42	G01J0003000000	Spectrometry; Spectrophotometry; Monochromators; Measuring colours	G01J0003420000	Absorption spectrometry; Double- beam spectrometry; Flicker spectrometry; Reflection spectrometry (beam-switching arrangements G01J0003080000)
G01N 21/78	G01N0021000000	Investigating or analysing materials by the use of optical means, i.e. using infra-red, visible or ultra-violet light (G01N0003000000- G01N0019000000 take precedence)	G01N0021780000	producing a change of colour
G01N 21/64	G01N0021000000	Investigating or analysing materials by the use of optical means, i.e. using infra-red, visible or ultra-violet light (G01N0003000000- G01N0019000000 take precedence)	G01N0021640000	Fluorescence; Phosphorescence
G01N 21/45	G01N0021000000	Investigating or analysing materials by the use of optical means, i.e. using infra-red, visible or ultra-violet light (G01N0003000000- G01N0019000000 take precedence)	G01N0021450000	using interferometric methods; using Schlieren methods
G01N 21/47	G01N0021000000	Investigating or analysing materials by the use of optical means, i.e. using infra-red, visible or ultra-violet light (G01N0003000000- G01N0019000000 take precedence)	G01N0021470000	Scattering, i.e. diffuse reflection (G01N0021250000, G01N0021410000 take precedence)

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G01N 21/17	G01N0021000000	Investigating or analysing materials by the use of optical means, i.e. using infra-red, visible or ultra-violet light (G01N0003000000-G01N0019000000 take precedence)	G01N0021170000	Systems in which incident light is modified in accordance with the properties of the material investigated (where the material investigated is optically excited causing a change in wavelength of the incident light G01N0021630000)
G01N 23/04	G01N0023000000	Investigating or analysing materials by the use of wave or particle radiation, e.g. X-rays or neutrons, not covered by groups G01N0003000000-G01N0017000000, G01N0021000000 or G01N0022000000	G01N0023040000	and forming images of the material
G01N 33/60	G01N0033000000	Investigating or analysing materials by specific methods not covered by groups G01N0001000000-G01N0031000000	G01N0033600000	involving radioactive labelled substances
G01N 33/48	G01N0033000000	Investigating or analysing materials by specific methods not covered by groups G01N0001000000-G01N0031000000	G01N0033480000	Biological material, e.g. blood, urine (G01N0033020000, G01N0033260000, G01N0033440000, G01N0033460000 take precedence); Haemocytometers (counting blood corpuscles distributed over a surface by scanning the surface G06M0011020000)

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G01N 33/50	G01N0033000000	Investigating or analysing materials by specific methods not covered by groups G01N0001000000-G01N0031000000	G01N0033500000	Chemical analysis of biological material, e.g. blood, urine; Testing involving biospecific ligand binding methods; Immunological testing (measuring or testing processes other than immunological involving enzymes or microorganisms, compositions or test papers therefor, processes of forming such compositions, condition responsive control in microbiological or enzymological processes C12Q)
G01R 33/563	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033563000	of moving material, e.g. flow-contrast angiography
G01R 33/24	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033240000	for measuring direction or magnitude of magnetic fields or magnetic flux
G01R 33/565	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033565000	Correction of image distortions, e.g. due to magnetic field inhomogeneities
G01R 33/483	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033483000	with selection of signal or spectra from particular regions of the volume, e.g. in vivo spectroscopy
G01R 33/56	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033560000	Image enhancement or correction, e.g. subtraction or averaging techniques
G01R 33/561	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033561000	by reduction of the scanning time, i.e. fast acquiring systems, e.g. using echo-planar pulse sequences

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G01R 33/50	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033500000	based on the determination of relaxation times
G01R 33/48	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033480000	NMR imaging systems
G01R 33/54	G01R0033000000	Arrangements or instruments for measuring magnetic variables	G01R0033540000	Signal processing systems, e.g. using pulse sequences
G01T 1/20	G01T0001000000	Measuring X-radiation, gamma radiation, corpuscular radiation, or cosmic radiation (G01T0003000000, G01T0005000000 take precedence)	G01T0001200000	with scintillation detectors
G01T 1/164	G01T0001000000	Measuring X-radiation, gamma radiation, corpuscular radiation, or cosmic radiation (G01T0003000000, G01T0005000000 take precedence)	G01T0001164000	Scintigraphy
G01T 1/24	G01T0001000000	Measuring X-radiation, gamma radiation, corpuscular radiation, or cosmic radiation (G01T0003000000, G01T0005000000 take precedence)	G01T0001240000	with semiconductor detectors
G01T 1/29	G01T0001000000	Measuring X-radiation, gamma radiation, corpuscular radiation, or cosmic radiation (G01T0003000000, G01T0005000000 take precedence)	G01T0001290000	Measurement performed on radiation beams, e.g. position or section of the beam; Measurement of spatial distribution of radiation
G01T 1/00	G01T0001000000	Measuring X-radiation, gamma radiation, corpuscular radiation, or cosmic radiation (G01T0003000000, G01T0005000000 take precedence)		

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G01V 3/00	G01V0003000000	Electric or magnetic prospecting or detecting; Measuring magnetic field characteristics of the earth, e.g. declination or deviation		
G06F 3/01	G06F0003000000	Input arrangements for transferring data to be processed into a form capable of being handled by the computer; Output arrangements for transferring data from processing unit to output unit, e.g. interface arrangements	G06F0003010000	Input arrangements or combined input and output arrangements for interaction between user and computer (G06F0003160000 takes precedence)
G06F 17/00	G06F0017000000	Digital computing or data processing equipment or methods, specially adapted for specific functions (information retrieval, database structures or file system structures therefor G06F0016000000)		
G06G 7/60	G06G0007000000	Devices in which the computing operation is performed by varying electric or magnetic quantities (neural networks for image data processing G06T; speech analysis or synthesis G10L)	G06G0007600000	for living beings, e.g. their nervous systems
G06K 9/62	G06K0009000000	Methods or arrangements for reading or recognizing printed or written characters or for recognizing patterns, e.g. fingerprints (methods or arrangements for graph-reading or for converting the pattern of mechanical parameters, e.g. force or presence, into electrical signals G06K0011000000; speech recognition G10L0015000000)	G06K0009620000	Methods or arrangements for recognition using electronic means

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G06K 9/00	G06K0009000000	Methods or arrangements for reading or recognizing printed or written characters or for recognizing patterns, e.g. fingerprints (methods or arrangements for graph-reading or for converting the pattern of mechanical parameters, e.g. force or presence, into electrical signals G06K0011000000;speech recognition G10L0015000000)		
G06N 3/06	G06N0003000000	Computer systems based on biological models	G06N0003060000	Physical realisation, i.e. hardware implementation of neural networks, neurons or parts of neurons
G06N 3/067	G06N0003000000	Computer systems based on biological models	G06N0003067000	using optical means
G06N 3/02	G06N0003000000	Computer systems based on biological models	G06N0003020000	using neural network models
G06N 3/08	G06N0003000000	Computer systems based on biological models	G06N0003080000	Learning methods
G06N 3/063	G06N0003000000	Computer systems based on biological models	G06N0003063000	using electronic means
G06N 3/04	G06N0003000000	Computer systems based on biological models	G06N0003040000	Architecture, e.g. interconnection topology
G06N 99/00	G06N0099000000	Subject matter not provided for in other groups of this subclass		
G06T 3/00	G06T0003000000	Geometric image transformation in the plane of the image		
G06T 7/00	G06T0007000000	Image analysis		
G06T 7/11	G06T0007000000	Image analysis	G06T0007110000	Region-based segmentation

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G06T 11/00	G06T0011000000	2D [Two Dimensional] image generation		
G08B 21/06	G08B0021000000	Alarms responsive to a single specified undesired or abnormal condition and not otherwise provided for	G08B0021060000	indicating a condition of sleep, e.g. anti-dozing alarms
G09B 7/00	G09B0007000000	Electrically-operated teaching apparatus or devices working with questions and answers		
G09B 19/04	G09B0019000000	Teaching not covered by other main groups of this subclass (teaching or practice apparatus for gun-aiming or gun-laying F41G0003260000)	G09B0019040000	Speaking (with audible presentation of the material to be studied G09B0005040000)
G09B 19/00	G09B0019000000	Teaching not covered by other main groups of this subclass (teaching or practice apparatus for gun-aiming or gun-laying F41G0003260000)		
G10L 15/02	G10L0015000000	Speech recognition (G10L0017000000 takes precedence)	G10L0015020000	Feature extraction for speech recognition; Selection of recognition unit
G10L 15/24	G10L0015000000	Speech recognition (G10L0017000000 takes precedence)	G10L0015240000	Speech recognition using non-acoustical features
G10L 15/04	G10L0015000000	Speech recognition (G10L0017000000 takes precedence)	G10L0015040000	Segmentation; Word boundary detection
G10L 17/26	G10L0017000000	Speaker identification or verification	G10L0017260000	Recognition of special voice characteristics, e.g. for use in lie detectors; Recognition of animal voices

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G10L 25/15	G10L0025000000	Speech or voice analysis techniques not restricted to a single one of groups G10L0015000000- G10L0021000000 (muting semiconductor-based amplifiers when some special characteristics of a signal are sensed by a speech detector, e.g. sensing when no signal is present, H03G0003340000)	G10L0025150000	the extracted parameters being formant information
G10L 25/66	G10L0025000000	Speech or voice analysis techniques not restricted to a single one of groups G10L0015000000- G10L0021000000 (muting semiconductor-based amplifiers when some special characteristics of a signal are sensed by a speech detector, e.g. sensing when no signal is present, H03G0003340000)	G10L0025660000	for extracting parameters related to health condition (detecting or measuring for diagnostic purposes A61B0005000000)
G11C 11/54	G11C0011000000	Digital stores characterised by the use of particular electric or magnetic storage elements; Storage elements therefor (G11C0014000000- G11C0021000000 take precedence)	G11C0011540000	using elements simulating biological cells, e.g. neuron
G16H 10/20	G16H0010000000	ICT specially adapted for the handling or processing of patient-related medical or healthcare data (for medical reports G16H0015000000;for therapies or health-improving plans G16H0020000000;for the handling or processing of medical images G16H0030000000)	G16H0010200000	for electronic clinical trials or questionnaires

Symbol	Group Code	Group Description	Subgroup Code	Subgroup Description
G16H 20/30	G16H0020000000	ICT specially adapted for therapies or health-improving plans, e.g. for handling prescriptions, for steering therapy or for monitoring patient compliance	G16H0020300000	relating to physical therapies or activities, e.g. physiotherapy, acupressure or exercising
G16H 20/70	G16H0020000000	ICT specially adapted for therapies or health-improving plans, e.g. for handling prescriptions, for steering therapy or for monitoring patient compliance	G16H0020700000	relating to mental therapies, e.g. psychological therapy or autogenous training
G16H 30/20	G16H0030000000	ICT specially adapted for the handling or processing of medical images (computerised tomography A61B0006030000)	G16H0030200000	for handling medical images, e.g. DICOM, HL7 or PACS
G16H 30/40	G16H0030000000	ICT specially adapted for the handling or processing of medical images (computerised tomography A61B0006030000)	G16H0030400000	for processing medical images, e.g. editing
G16H 50/30	G16H0050000000	ICT specially adapted for medical diagnosis, medical simulation or medical data mining; ICT specially adapted for detecting, monitoring or modelling epidemics or pandemics	G16H0050300000	for calculating health indices; for individual health risk assessment
G16H 50/20	G16H0050000000	ICT specially adapted for medical diagnosis, medical simulation or medical data mining; ICT specially adapted for detecting, monitoring or modelling epidemics or pandemics	G16H0050200000	for computer-aided diagnosis, e.g. based on medical expert systems
H04R 25/00	H04R0025000000	Deaf-aid sets		
H04R 29/00	H04R0029000000	Monitoring arrangements; Testing arrangements		

Table 11. Prominent IPC combinations in neurotechnology patents

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
G02B 6/00	Light guides; Structural details of arrangements comprising light guides and other optical elements, e.g. couplings	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	15
H01L 21/00	Processes or apparatus specially adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	8
H02J 50/00	Circuit arrangements or systems for wireless supply or distribution of electric power	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	8
A61N 1/00	Electrotherapy; Circuits therefor (A61N0002000000 takes precedence;electrically conductive preparations for use in therapy or testing in vivoA61K0050000000)	G16H 50/00	ICT specially adapted for medical diagnosis, medical simulation or medical data mining; ICT specially adapted for detecting, monitoring or modelling epidemics or pandemics	6
H01S 3/00	Lasers, i.e. devices using stimulated emission of electromagnetic radiation in the infrared, visible or ultraviolet wave range (semiconductors lasers H01S0005000000)	G05B 13/00	Adaptive control systems, i.e. systems automatically adjusting themselves to have a performance which is optimum according to some preassigned criterion (G05B0019000000 takes precedence;machine learning G06N0020000000)	13
H01L 43/00	Devices using galvano-magnetic or similar magnetic effects; Processes or apparatus specially adapted for the manufacture or treatment thereof or of parts thereof (devices consisting of a plurality of solid state components formed in or on a common substrate H01L0027000000)	G06N 3/00	Computer systems based on biological models	9

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
H01G 9/00	Electrolytic capacitors, rectifiers, detectors, switching devices, light-sensitive or temperature-sensitive devices; Processes of their manufacture	G06N 3/00	Computer systems based on biological models	8
H01S 3/00	Lasers, i.e. devices using stimulated emission of electromagnetic radiation in the infrared, visible or ultraviolet wave range (semiconductors lasers H01S0005000000)	G06F 17/00	Digital computing or data processing equipment or methods, specially adapted for specific functions (information retrieval, database structures or file system structures therefor G06F0016000000)	7
G06T 7/00	Image analysis	A61B 8/00	Diagnosis using ultrasonic, sonic or infrasonic waves	16
G01L 5/00	Apparatus for, or methods of, measuring force, e.g. due to impact, work, mechanical power, or torque, adapted for special purposes	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	5
G01N 21/00	Investigating or analysing materials by the use of optical means, i.e. using infra-red, visible or ultra-violet light (G01N0003000000-G01N0019000000 take precedence)	C12Q 1/00	Measuring or testing processes involving enzymes, nucleic acids or microorganisms (measuring or testing apparatus with condition measuring or sensing means, e.g. colony counters, C12M0001340000); Compositions therefor; Processes of preparing such compositions	19

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
C12N 15/00	Mutation or genetic engineering; DNA or RNA concerning genetic engineering, vectors, e.g. plasmids, or their isolation, preparation or purification; Use of hosts therefor (mutants or genetically engineered microorganisms C12N0001000000, C12N0005000000, C12N0007000000;new plants A01H;plant reproduction by tissue culture techniques A01H0004000000;new animals A01K0067000000;use of medicinal preparations containing genetic material which is inserted into cells of the living body to treat genetic diseases, gene therapy A61K0048000000;peptides in general C07K)	A61K 31/00	Medicinal preparations containing organic active ingredients	12
A61F 2/00	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000;dental prostheses A61C0013000000;materials for prostheses A61L0027000000;artificial hearts A61M0001100000;artificial kidneys A61M0001140000)	G06N 7/00	Computer systems based on specific mathematical models	12
A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	G06N 7/00	Computer systems based on specific mathematical models	9

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
A61F 2/00	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000; dental prostheses A61C0013000000; materials for prostheses A61L0027000000; artificial hearts A61M0001100000; artificial kidneys A61M0001140000)	G06F 3/00	Input arrangements for transferring data to be processed into a form capable of being handled by the computer; Output arrangements for transferring data from processing unit to output unit, e.g. interface arrangements	9
A61F 2/00	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000; dental prostheses A61C0013000000; materials for prostheses A61L0027000000; artificial hearts A61M0001100000; artificial kidneys A61M0001140000)	G05B 19/00	Programme-control systems (specific applications, see the relevant places, e.g. A47L0015460000; clocks with attached or built-in means operating any device at a preselected time interval G04C0023000000; marking or sensing record carriers with digital information G06K; information storage G11; time or time-programme switches which automatically terminate their operation after the programme is completed H01H0043000000)	8
H04R 29/00	Monitoring arrangements; Testing arrangements	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	4

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
H04R 25/00	Deaf-aid sets	A61M 21/00	Other devices or methods to cause a change in the state of consciousness; Devices for producing or ending sleep by mechanical, optical, or acoustical means, e.g. for hypnosis (beds for promoting sleep A61G0007043000)	4
A61F 11/00	Methods or devices for treatment of the ears, e.g. surgical; Protective devices for the ears, carried on the body or in the hand (headwear, e.g. caps or helmets, with means for protecting the ears A42B0001060000, A42B0003160000)	H04R 1/00	Details of transducers (diaphragms H04R0007000000; characterised by the nature of the transducer, see the relevant group of main groups H04R0009000000- H04R0023000000; mountings specially adapted for telephone equipment H04M0001020000)	3
G09B 21/00	Teaching, or communicating with, the blind, deaf or mute (audible presentation of material to be studied G09B0005040000)	A61F 11/00	Methods or devices for treatment of the ears, e.g. surgical; Protective devices for the ears, carried on the body or in the hand (headwear, e.g. caps or helmets, with means for protecting the ears A42B0001060000, A42B0003160000)	2
A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	B60N 2/00	Seats specially adapted for vehicles; Arrangement or mounting of seats in vehicles (railway seats B61D0033000000; cycle seats B62J0001000000; aircraft seats B64D0011060000, B64D0025040000, B64D0025100000)	14
B60K 28/00	Safety devices for propulsion-unit control, specially adapted for, or arranged in, vehicles, e.g. preventing fuel supply or ignition in the event of potentially dangerous conditions (for electrically-propelled vehicles B60L0003000000; road vehicle drive control systems for purposes not related to the control of a particular sub-unit B60W0030000000)	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	7

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000;diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	G16H 30/00	ICT specially adapted for the handling or processing of medical images (computerised tomography A61B0006030000)	5
B25J 19/00	Accessories fitted to manipulators, e.g. for monitoring, for viewing; Safety devices combined with or specially adapted for use in connection with manipulators (safety devices in general F16P;protection against radiation in general G21F)	A61F 2/00	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000; dental prostheses A61C0013000000; materials for prostheses A61L0027000000;artificial hearts A61M0001100000;artificial kidneys A61M0001140000)	6
A61B 34/00	Computer-aided surgery; Manipulators or robots specially adapted for use in surgery	B25J 9/00	Programme-controlled manipulators	5
G05B 21/00	Systems involving sampling of the variable controlled (G05B0013000000-G05B0019000000 take precedence; transmission systems for measured values G08C;electronic switching or gating H03K0017000000)	A61F 2/00	Filters implantable into blood vessels; Prostheses, i.e. artificial substitutes or replacements for parts of the body; Appliances for connecting them with the body; Devices providing patency to, or preventing collapsing of, tubular structures of the body, e.g. stents (as cosmetic articles, see the relevant subclasses, e.g. wigs, hair pieces, A41G0003000000, A41G0005000000, artificial nails A45D0031000000;dental prostheses A61C0013000000;materials for prostheses A61L0027000000;artificial hearts A61M0001100000;artificial kidneys A61M0001140000)	5

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
G09B 5/00	Electrically-operated educational appliances	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	14
G06Q 10/00	Administration; Management	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	14
H04W 12/00	Security arrangements, e.g. access security or fraud detection; Authentication, e.g. verifying user identity or authorisation; Protecting privacy or anonymity (arrangements for secret or secure communication H04L0009000000)	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	12
G01N 23/00	Investigating or analysing materials by the use of wave or particle radiation, e.g. X-rays or neutrons, not covered by groups G01N0003000000-G01N0017000000, G01N0021000000 or G01N0022000000	H01J 49/00	Particle spectrometers or separator tubes	5
G21K 1/00	Arrangements for handling particles or ionising radiation, e.g. focusing or moderating (ionising radiation filters G21K0003000000; production or acceleration of neutrons, electrically-charged particles, neutral molecular beams or neutral atomic beams H05H0003000000-H05H0015000000)	H01J 49/00	Particle spectrometers or separator tubes	4
G01B 9/00	Instruments as specified in the subgroups and characterised by the use of optical measuring means (arrangements for measuring particular parameters G01B0011000000)	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	4

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
G06T 7/00	Image analysis	A61B 3/00	Apparatus for testing the eyes; Instruments for examining the eyes (eye inspection using ultrasonic, sonic or infrasonic waves A61B0008100000)	3
H01S 5/00	Semiconductor lasers (superluminescent diodes H01L0033000000)	G01N 21/00	Investigating or analysing materials by the use of optical means, i.e. using infra-red, visible or ultra-violet light (G01N0003000000-G01N0019000000 take precedence)	2
G01R 33/00	Arrangements or instruments for measuring magnetic variables	A61B 10/00	Other methods or instruments for diagnosis, e.g. for vaccination diagnosis; Sex determination; Ovulation-period determination; Throat striking implements	5
G01R 33/00	Arrangements or instruments for measuring magnetic variables	A61K 49/00	Preparations for testing in vivo	3
G10L 17/00	Speaker identification or verification	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	5
B26D 1/00	Cutting through work characterised by the nature or movement of the cutting member; Apparatus or machines therefor; Cutting members therefor	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	5
A61N 5/00	Radiation therapy (devices or apparatus applicable to both therapy and diagnosis A61B0006000000; applying radioactive material to the body A61M0036000000)	G06N 3/00	Computer systems based on biological models	2
G01N 24/00	Investigating or analysing materials by the use of nuclear magnetic resonance, electron paramagnetic resonance or other spin effects	A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	2

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	G16H 10/00	ICT specially adapted for the handling or processing of patient-related medical or healthcare data (for medical reports G16H0015000000; for therapies or health-improving plans G16H0020000000; for the handling or processing of medical images G16H0030000000)	2
A61B 5/00	Measuring for diagnostic purposes (radiation diagnosis A61B0006000000; diagnosis by ultrasonic, sonic or infrasonic waves A61B0008000000); Identification of persons	G06G 7/00	Devices in which the computing operation is performed by varying electric or magnetic quantities (neural networks for image data processing G06T; speech analysis or synthesis G10L)	2
A61B 10/00	Other methods or instruments for diagnosis, e.g. for vaccination diagnosis; Sex determination; Ovulation-period determination; Throat striking implements	G16H 10/00	ICT specially adapted for the handling or processing of patient-related medical or healthcare data (for medical reports G16H0015000000; for therapies or health-improving plans G16H0020000000; for the handling or processing of medical images G16H0030000000)	1
A61B 6/00	Apparatus for radiation diagnosis, e.g. combined with radiation therapy equipment (instruments measuring radiation intensity for application in the field of nuclear medicine, e.g. in vivo counting, G01T0001161000; apparatus for taking X-ray photographs G03B0042020000)	H05G 1/00	X-ray apparatus involving X-ray tubes; Circuits therefor	10
A61B 6/00	Apparatus for radiation diagnosis, e.g. combined with radiation therapy equipment (instruments measuring radiation intensity for application in the field of nuclear medicine, e.g. in vivo counting, G01T0001161000; apparatus for taking X-ray photographs G03B0042020000)	G01N 23/00	Investigating or analysing materials by the use of wave or particle radiation, e.g. X-rays or neutrons, not covered by groups G01N0003000000-G01N0017000000, G01N0021000000 or G01N0022000000	7

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
H04N 5/00	Details of television systems (scanning details or combination thereof with generation of supply voltages H04N0003000000)	G01T 1/00	Measuring X-radiation, gamma radiation, corpuscular radiation, or cosmic radiation (G01T0003000000, G01T0005000000 take precedence)	5
G01T 1/00	Measuring X-radiation, gamma radiation, corpuscular radiation, or cosmic radiation (G01T0003000000, G01T0005000000 take precedence)	H05G 1/00	X-ray apparatus involving X-ray tubes; Circuits therefor	3
G06T 11/00	2D [Two Dimensional] image generation	A61B 6/00	Apparatus for radiation diagnosis, e.g. combined with radiation therapy equipment (instruments measuring radiation intensity for application in the field of nuclear medicine, e.g. in vivo counting, G01T0001161000; apparatus for taking X-ray photographs G03B0042020000)	2
A61B 6/00	Apparatus for radiation diagnosis, e.g. combined with radiation therapy equipment (instruments measuring radiation intensity for application in the field of nuclear medicine, e.g. in vivo counting, G01T0001161000; apparatus for taking X-ray photographs G03B0042020000)	H04N 5/00	Details of television systems (scanning details or combination thereof with generation of supply voltages H04N0003000000)	2
A61K 47/00	Medicinal preparations characterised by the non-active ingredients used, e.g. carriers or inert additives; Targeting or modifying agents chemically bound to the active ingredient	G01N 33/00	Investigating or analysing materials by specific methods not covered by groups G01N0001000000-G01N0031000000	8
C07D 211/00	Heterocyclic compounds containing hydrogenated pyridine rings, not condensed with other rings	A61K 51/00	Preparations containing radioactive substances for use in therapy or testing in vivo	8
C07B 59/00	Introduction of isotopes of elements into organic compounds	A61K 51/00	Preparations containing radioactive substances for use in therapy or testing in vivo	7

Group Code	Group Description	Pair Group Code	Pair Group Description	Count
C07D 217/00	Heterocyclic compounds containing isoquinoline or hydrogenated isoquinoline ring systems	A61K 51/00	Preparations containing radioactive substances for use in therapy or testing in vivo	5
C07D 215/00	Heterocyclic compounds containing quinoline or hydrogenated quinoline ring systems	A61K 51/00	Preparations containing radioactive substances for use in therapy or testing in vivo	5
A61K 47/00	Medicinal preparations characterised by the non-active ingredients used, e.g. carriers or inert additives; Targeting or modifying agents chemically bound to the active ingredient	C07D 277/00	Heterocyclic compounds containing 1,3-thiazole or hydrogenated 1,3-thiazole rings	4
C07B 59/00	Introduction of isotopes of elements into organic compounds	A61K 47/00	Medicinal preparations characterised by the non-active ingredients used, e.g. carriers or inert additives; Targeting or modifying agents chemically bound to the active ingredient	4
C07B 59/00	Introduction of isotopes of elements into organic compounds	G01N 33/00	Investigating or analysing materials by specific methods not covered by groups G01N0001000000-G01N0031000000	4
A61K 51/00	Preparations containing radioactive substances for use in therapy or testing in vivo	G01N 33/00	Investigating or analysing materials by specific methods not covered by groups G01N0001000000-G01N0031000000	4
A61K 51/00	Preparations containing radioactive substances for use in therapy or testing in vivo	C07D 277/00	Heterocyclic compounds containing 1,3-thiazole or hydrogenated 1,3-thiazole rings	4

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Unveiling the Neurotechnology Landscape

Scientific Advancements
Innovations and Major Trends

Diving into the fascinating world of neurotechnology, this publication offers first time solid evidence about the complex neurotechnology landscape, unveiling global scientific advancements, innovations, innovators, and major trends. The analysis relies on a novel approach that leverages Artificial Intelligence on data about scientific publications and patents.

Neurotechnology's complexity and potential stems from its being at the intersection between disciplines including neuroscience, chemistry, biotechnology, computer science, pharmaceuticals, medical technology. The promises that neurotechnology holds to help people with disabilities are as big as the ethical concerns they raise, if abused, as neurotechnology can affect our identity, autonomy, privacy, sentiments, behaviors and overall well-being, i.e. our being humans.

However, the design of a well-crafted, effective governance model for neurotechnology needs to be informed by a comprehensive understanding of the scientific and technological landscape. This is what this publication proposes, in support of the policy discussion of our 194 Member States.



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