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The European University
of Brain and Technology

D4.5 in WP4

Cooperation models including the sustainable regional development

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D4.5 in WP4 Cooperation models including the sustainable regional development

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Table of Contents

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Introduction

The Strategy and Action Plan, or policy development, this deliverable serves for,

(I) is in concert with the following key characteristics:

- NeurotechEU has been complemented by NeurotechRI, a project funded under a "Science with and for Society" initiative in such a way that infrastructures, including not only shared research mediums/platforms but also **policies** to characterize the research and technological as well as societal innovation strategies of NeurotechEU are formed.
- In concert with that to characterize NeurotechEU's Common Policies and Strategy Development Work Package actions and to design those specifically related to the series of deliverables *Cooperation models including the sustainable regional development* and *Translation of innovations into the industry*, societal initiatives including, but not limited to the issues, *usefulness for the society*, *innovation of the society*, *training of the future neurotechnology experts and supplementing experts that are currently in action, with a broader socio-technological citizenship skill sets* are made a priority and operationalized comprehensively in this deliverable.

(II) and is comprised of the following essential elements:

- From Science with and for Society (SwafS) Initiative to the Transdisciplinarity Concept
- Bibliometric Analyses to Identify State-of-the-Art Research in Neurotechnology Globally
- Understanding Societal Challenges Questionnaire: NeurotechEU's innovative approach to identifying what society wants
- Integrating Societal Needs Knowledge into the Scientific Process to Characterize the NeurotechEU's Strategy for Translational R&I and Collaboration
- Smart Specialization Strategy Concept as the key policy flowchart to be utilized being supplemented and enhanced with authentic NeurotechEU methodologies

From Science with and for Society (SwafS) Initiative to the Transdisciplinarity Concept

Since NeurotechEU grew out of a project funded under a "Science with and for Society" (SwafS) initiative, it is important that societal initiatives must be understood and the technologies that will be developed with the help of scientific research must be tailored to the needs of the society. This also requires that existing regional development/RTDI ecosystem data and analysis be fully leveraged, e.g., by developing regional Smart Specialization Strategies that are ERDF-funded.

One of the main aims of SwafS should be the establishment of the well-being of the people living in an area. There are different aspects of well-being including (What Is Well-Being? Definition, Types, and Well-

Being Skills, https://www.psychologytoday.com/us/blog/click-here-for-happiness/201901/what-is-well-being-definition-types-and-well-being-skills):

- Emotional well-being: The capacity to manage stress, implement relaxation techniques, demonstrate resilience, and foster positive emotions.
- Physical well-being: The ability to enhance bodily functions through healthy lifestyle choices and consistent exercise.
- Social well-being: The skill to communicate effectively, cultivate meaningful relationships, and sustain a supportive network to mitigate loneliness.
- Workplace well-being: The ability to align personal interests, values, and life purpose to achieve professional fulfillment, meaning, and happiness.
- Societal well-being: The capacity to actively contribute to and engage with a thriving community, culture, and environment.

Societal well-being, for people living in both urban and rural areas, requires intelligent design of public spaces, mobility, access, and transportation that are tailored to the needs of individuals. In this context, the notion of Society 5.0, which was proposed in Japan with the aim of forming a sustainable societal environment and enhancing residents' comfort with enriched technological opportunities, is based on the integration of physical space and cyberspace in a balanced way through technological advancements such as the Internet of Things (IoT), blockchains, edge computing, and machine learning algorithms (Kiruthika et al., 2024). Another term used for Society 5.0 is human-centric super-smart society. This concept has also impacted Industry 4.0, which primarily focuses on technological advances to form smart infrastructures such as smart transportation, smart buildings, smart factories, and smart healthcare, transforming it into Industry 5.0, where the societal well-being of humans is centered by respecting their working conditions (Coronado et al., 2022). In other words, all the smart infrastructures are established with a human-centric focus, paying attention to human-machine interaction and interfaces. This, in turn, brings the topics of societal values and human well-being issues to the forefront in addition to the economic considerations and efficiency issues of Industry 4.0 (Alter, 2020). It has been well understood that technological advances in areas such as transportation, healthcare, communication, education, and manufacturing, while significant, are insufficient and ineffective for sustainable development without considering human factors. Therefore, it is crucial to integrate the human dimension alongside various technological tools and systems such as IoT, big data, and machine learning algorithms. This necessity brings neurotechnology into play. Neurotechnology, by interacting with the human brain and nervous system, enables technological systems to become more aligned with human needs. Therefore, to cope with neurochallenges, principles of cognition and neuroscience must be used to comprehend and anticipate human behavior. Appropriate solutions are then devised and implemented utilizing neurotechnologies to enhance the quality of life and well-being for present and future generations. This, however, requires the following conditions:

- Transdisciplinary research carried out at the partner universities to develop new tools based on understanding the societal challenges and integration of this knowledge into the scientific process. As Jantsch (1970) points out, the university is expected to develop increasingly interdisciplinary approaches so that the entire education/innovation system may become coordinated as a multilevel multigoal hierarchical system through a transdisciplinary approach.

- Devising educational strategies that aim to address societal challenges/innovate our societies.
- Strengthening cooperation with companies institutionalizing cooperation among NeurotechEU partner universities and industry-associated partners
- Linking the eight dimensions of neurotechnology, particularly D8: Neurometaphysics to regional development by considering socio-economic, environmental, and cultural needs in a manner that would also serve the UN Sustainable Development Goals (SDGs).
- Developing challenge-, society-, and technology-based roadmaps for translation of innovations into the industry and market

Bibliometric Analyses to Identify State-of-the-Art R&I in Neurotechnology Globally

In order to objectively assess the state of the art in the field of neurotechnology it is key to identify the most prominent **challenges**, which include neurological disorders (such as stroke, Parkinson's disease, Alzheimer's disease, multiple sclerosis, depression, addiction, and many more) in the subject area of Medicine but also numerous others in the additional subject areas of Engineering, Computer Science, Environmental Science, and Social Sciences as well as Neuroscience. Furthermore, for those challenges with potential medical, economic, and societal impact it is also central to characterize the **technologies** that are utilized globally to provide solutions. To locate those challenges and technologies with the intention to also seek their relationships or a lack thereof, a detailed bibliometric analysis has been conducted.

Methods

Bibliometric Analyses

NeurotechEU defined 8 dimensions to classify different education and research actions in the broad field of neurotechnology: D1 – Empirical and clinical neuroscience, D2 – Theoretical neuroscience, D3 – Neuromorphic computing, D4 – Neuromorphic control/neurorobotics, D5 – Neuroinformatics, D6 – Neuroprosthetics, D7 – Clinical neurotechnology, D8 – Neurometaphysics.

The bibliometric analyses per neurotechnology dimension starts with an initial list of terms/themes related to each. Those lists are then finalized (referred to as **Keywords Utilized**) based on the suggestions of domain experts. An exemplary list is shown below for D4:

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

Note that the abbreviations shown in parentheses are not used in the queries but are provided for comprehensiveness.

The set of keywords utilized were then fed into a search in the Scopus database for each dimension. The Scopus database was preferred over Web of Science due to its larger number of indexed journals. Queries were used to locate journal articles, reviews, and conference papers that contained these keywords in their title, abstract, or author-defined keywords. One practical disadvantage of Scopus is that it only allows 2000 documents at a time to be imported as a .csv file. This may require repeating the procedure many times for tens or hundreds of thousands of documents. To keep the workload manageable, the recent, full year of 2022 was opted to be studied. Note also that only publications in the English language were considered. Bibliometric analyses can be done with various purposes with reference to authors, research institutions, and countries that produce the documents. However, here the aim was to identify the global R&I trends in neurotechnology, hence, the author-defined keywords existing in the published documents were retrieved. Subsequently, a co-word analysis, also known as "author keyword co-occurrence analysis," was performed per neurotechnology dimension studied and according to the following rule: the documents found in the most prominent three subject areas, e.g., Medicine, Biochemistry, Genetics and Molecular Biology, Engineering, and Computer Science were considered and in addition, the subject area Neuroscience was also considered due to its importance for NeurotechEU. The co-occurrence analysis was carried out in VOSviewer software. This method counts the author-defined keywords used in the documents as well as the number of times these keywords are used together in two different documents. The keywords are then visualized in a network where the nodes represent the keywords and the links between a pair of nodes designate the co-occurrence relationship between two keywords. The size of the nodes measures the number of occurrences of a keyword in the documents while the width of the link measures the number of co-occurrences of a pair of nodes, i.e., the strength of the relationship.

The keywords that bare the same meaning (e.g., "Data analytic" and "data analytics") were merged into one. Although this causes a certain decrease in the number of retrieved keywords, the challenge remains to visualize the keywords in a network in the co-word analysis. Therefore, by increasing the "minimum

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number of occurrences of a keyword" threshold in the VOSviewer software, the number of keywords represented in the co-word analysis was set to 100.

The results of the co-word analysis are analyzed and shown below in dedicated figures per neurotechnology dimension and per subject area studied. In addition to the nodes and links representing, respectively, the number of occurrences of the keywords separately and the number of co-occurrences of a pair of keywords, the VOSviewer software also clustered the keywords based on the association strength between the keywords. For this purpose, the VOSviewer's clustering algorithm was used (with the counting method fractional counting, and the normalization method based on association strength). The number of clusters can be chosen parametrically, and, in the present analysis, this was set to five considering that this allows a meaningful representation to interpret the thematic groups. Note that each color in the network displayed in co-word analysis figures represents a distinct thematic cluster. The nodes and links within a cluster help explain the range of topics (nodes) covered by that theme (cluster) and how those topics (nodes) are interconnected (links) (Donthu et al., 2021).

Examples of Bibliometric Analyses over Selected Neurotechnology Dimensions

Bibliometric analyses of Dimension 4: Neuromorphic Control/Neurorobotics and Dimension 5: Neuroinformatics as neurotechnology dimensions, which reveal the representative potential of translational R&I, as well as of the field of Smart Cities were conducted. With these three fields, both technical and societal aspects that play a role in developing our NeurotechEU's Cooperation models including the sustainable regional development can be exemplified. Through this we aim at fueling such policymaking that suits the vision of a European University's integration with industry as well as other relevant regional stakeholders and developing implementable cooperation models with the authentic information NeurotechEU develops. Here, transdisciplinarity should be key instead of planning actions based on conducting discipline-specific research and innovation, i.e., extending what is already done. Transdisciplinarity, being a process that is inherently complex and challenging, was originally defined as the coordination of all disciplines and inter-disciplines within an education/innovation system based on common objectives to deliver on the purpose of societal self-renewal (Jantsch, 1970). Smart Cities is a great example for an interdisciplinary or transdisciplinary and highly challenging field and is a part of Dimension 8 (i.e., Neurometaphysics) although it is an overarching field with interaction with several other neurotechnology dimensions NeurotechEU has defined. More importantly, it is a field that necessitates decision-making processes towards achieving improved human skills and better functioning by considering the urban context, ethical principles, societal rights, and human-centricity with a sensitive approach to managing and ideally diminishing socio-environmental challenges. Of course, efficient utilization of resources is also central.

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Outcomes

(I) Dimension 4: Neuromorphic Control/Neurorobotics

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

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

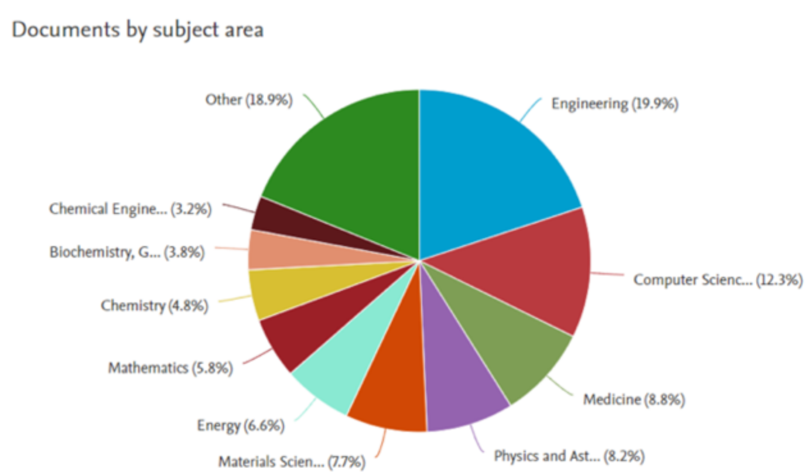

Figure 1. Pie chart illustrating the percentage weight of subject areas in the field of Neuromorphic Control/Neurorobotics.

Documents by Subject Area The search resulted in 1,050,568 documents. Figure 2 shows the distribution of documents with respect to the subject areas. The most prominent subject area is **Engineering**, which contains 209,063 documents that account for 19.9% of the overall number of documents. **Computer Science** ranks second with 129,366 documents and **Medicine** ranks third with

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122,773 documents, whereas **Neuroscience** with 29,428 documents appears within the group of subject areas referred to as Others.

Engineering (Figure 2) and **Computer Science** (Figure 3) are technology dominant subject areas. AI-based technologies, Internet of Things (IoT), and sensor technologies are key technologies in the dimension of neurorobotics. Challenges studied in this dimension include electric vehicle, autonomous vehicles, unmanned aerial vehicles, and energy-related challenges (renewable energy, energy storage, energy efficiency, energy harvesting, power quality) as well as reliability and security. As AI-based technologies are applied as a solution to challenges and are characteristic technologies for neurotechnology, they are relevant for this dimension. The same is valid for sensor technologies and IoT since neurotechnology is largely about collection of data (via e.g., sensors) and collection/communication of that to be used in algorithm development (AI-based technologies are utilized here) to finally obtain context-aware decision-making. Therefore, the findings suggest that the most common challenges in the dimension of neurorobotics and the most common technologies are in concert.

However, (1) the above observation can also be considered trivial or at least predictable, and the complementarity of energy-related challenges in particular and the revealed key technologies needs to be studied in more detail. (2) More importantly, as the revealed key technologies are studied widely across the globe, regardless of their association with challenges, the less studied, notable technologies can be considered to bare more potential for making an impact in translational innovation and can lead to numerous collaboration models between university and industry in various regions of NeurotechEU. These notable technologies include optimization, lithium-ion batteries, virtual reality, wireless sensor network, wireless power transfer, smart grid, block chain, 5G, finite element analysis, additive manufacturing, robotics, biomechanics, and EEG. (3) Another notable observation is the lack of health- and health care-related challenges among those studied in Engineering and Computer Science subject areas. Whereas, the notable technologies that are studied in those subject areas do have an association with challenges related to human movement (e.g., biomechanics, virtual reality, robotics, EEG, finite element analysis, etc.) and/or to devices that provide solutions to such pathological conditions (battery technologies, wireless sensor/power transfer technologies, additive manufacturing technologies, etc.) that can be used in motion-assistive devices such as exoskeletons, smart prosthetic devices, wearable technologies, etc.

This gap nevertheless is filled in the subject area of **Medicine** (Figure 4), which is a technology and challenge mixed subject area. The key challenges studied in this area are stroke related (stroke, atrial fibrillation, ischemic stroke, heart failure), Parkinson's disease, multiple sclerosis, autism, children, mortality, depression, outcome, cardiovascular disease, and quality of life. The key technologies include, as expected, AI-based technologies with also medical imaging technologies (e.g., MRI) and prognosis being the most studied globally. With the inclusion of notable technologies, including biomarkers, rehabilitation, meta-analysis, EEG, biomechanics, diagnosis, and virtual reality, research in the field of Medicine appears to show a good relationship between challenges and technology development to provide solutions. However, the translational innovation aspect of this coherence needs to be studied in more detail. **Yet, it is clearly apparent that a transdisciplinary collaboration between Engineering, Computer Science, and Medicine subject areas can also allow the first two of the most studied subject areas to also provide**

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solutions to health- and health care-related challenges. Collaboration models to be established via that path have a great potential to impact the industry and economy. Yet, the bibliometric analyses conducted, and the deduced R&I directions are still incapable of indicating if those solutions will be the ones which society needs.

Finally, **Neuroscience** (Figure 5) is a challenge dominant subject area. The challenges studied in Neuroscience coupled with those addressed in Medicine, do yield a highly comprehensive list of health- and health care-related problems to be tackled: Parkinson's disease, stroke, multiple sclerosis, autism, Alzheimer's disease, ischemic stroke, epilepsy, cognition, depression, neuroinflammation, inflammation, neurodegeneration, dementia, and aging. The key technologies studied (EEG, AI-based technologies, and MRI, and the notable technologies including TMS, functional connectivity, ERP, neuromodulation, meta-analysis, rehabilitation, deep brain stimulation, gait, balance, electromyography, and brain-computer interface) are also fully complementary to what is said above. One important note is the following: the Neuroscience subject area comprises only a small portion of the globally conducted research in the dimension of neurorobotics. However, regarding **health- and health care-related challenges, it shows a prominent relationship between challenges and solution-providing technologies. Yet, again, the translational innovation aspect is unclear and the deduced R&I directions are still incapable of indicating if the solutions developed will be the ones which society needs.**

Engineering (209,063 documents, 88,740 author keywords)

A technology dominant subject area

The most occurring keyword is **machine learning**

Technology/Challenge	Occurrences
machine learning	4825
deep learning	4028
internet of things	3751
artificial neural network	3520
sensor	2228
electric vehicle	2199
optimization	2183
convolutional neural network	2083
renewable energy	2056
neural network	1996
lithium-ion battery	1842
virtual reality	1592
wireless sensor network	1582
artificial intelligence	1490
autonomous vehicles	1425
energy storage	1282
microgrid	1240
energy efficiency	1179
smart grid	1142
reinforcement learning	998
reliability	938
simulation	933
wireless power transfer	917
finite element analysis	907
energy harvesting	886
genetic algorithm	885
photovoltaic	874
power quality	856
model predictive control	848

Key technologies:
AI-based (machine learning, deep learning, artificial neural network, CNN, NN, artificial intelligence), IoT, sensor

Notable technologies:
Optimization, lithium-ion battery, virtual reality, wireless sensor network, wireless power transfer, finite element analysis, additive manufacturing, robotics, biomechanics

Key challenges:
Electric vehicle, renewable energy, autonomous vehicles, energy storage, energy efficiency, reliability, energy harvesting, power quality

Figure 2. Results of bibliometric analyses in D4 Neuromorphic Control/Neurorobotics in the Engineering subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 30 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies as well as key challenges.

Computer Science (129,366 documents , 74,858 author keywords)

A technology dominant subject area

The most occurring keyword is **IoT**

Technology/Challenge	Occurrences
internet of things	4967
machine learning	4758
deep learning	4566
virtual reality	2658
artificial neural network	2561
convolutional neural network	2204
wireless sensor network	2010
neural network	1848
sensor	1647
artificial intelligence	1617
autonomous vehicle	1444
optimization	1424
EEG	1367
robotics	1140
reinforcement learning	1100
unmanned aerial vehicles	1072
electric vehicle	1020
energy efficiency	995
security	959
smart grid	903
blockchain	864
edge computing	816
classification	766
long short-term memory	702
5G	677
renewable energy	664
feature extraction	654
computer vision	651
simulation	625

Key technologies:
IoT, AI-based (machine learning, deep learning, artificial neural network, CNN, NN, AI, reinforcement learning LSTM, feature extraction), wireless sensor network, sensor

Notable technologies:
Optimization, EEG, robotics, smart grid, block chain, 5G

Key challenges:
Autonomous vehicle, unmanned aerial vehicles, electric vehicle, energy efficiency, security, renewable energy

Figure 3. Results of bibliometric analyses in D4 Neuromorphic Control/Neurorobotics in the Computer Science subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 30 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies as well as key challenges.

Medicine (122,773 documents, 86,808 author keywords)

A technology and challenge mixed subject area

The most occurring keyword is **machine learning**

Technology/Challenge	Occurrences
machine learning	6481
stroke	5165
artificial intelligence	3442
deep learning	3391
covid-19	2942
Parkinson's disease	2459
multiple sclerosis	2415
autism	2167
MRI	1884
prognosis	1548
atrial fibrillation	1488
ischemic stroke	1425
biomarker	1402
rehabilitation	1385
heart failure	1341
children	1197
meta-analysis	1080
mortality	1080
EEG	1059
biomechanics	1006
CNN	995
depression	988
diagnosis	949
outcome	930
cardiovascular disease	912
virtual reality	893
quality of life	881
systematic review	847
inflammation	789

Key technologies:
AI-based (machine learning, artificial intelligence, deep learning, CNN), MRI, prognosis

Notable technologies:
Biomarker, rehabilitation, meta-analysis, EEG, biomechanics, diagnosis, virtual reality, inflammation

Key challenges:
Stroke related (stroke, atrial fibrillation, ischemic stroke, heart failure), Covid-19, Parkinson’s disease, multiple sclerosis, autism, children, mortality, depression, outcome, cardiovascular disease, quality of life

Figure 4. Results of bibliometric analyses in D4 Neuromorphic Control/Neurorobotics in the Medicine subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 30

keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies as well as key challenges.

Neuroscience (29,428 documents, 26,997 author keywords)

A challenge dominant subject area

The most occurring keyword is IoT

Technology/Challenge	Occurrences
Parkinson's disease	2126
stroke	1511
multiple sclerosis	1464
EEG	1442
autism	1049
machine learning	815
Alzheimer's disease	642
ischemic stroke	613
MRI	565
epilepsy	486
biomarker	466
deep learning	455
cognition	451
covid-19	393
fMRI	377
depression	368
TMS	346
neuroinflammation	338
inflammation	315
functional connectivity	314
ERP	306
neuromodulation	300
meta-analysis	298
rehabilitation	295
neurodegeneration	279
dementia	277
aging	271
deep brain stimulation	266
schizophrenia	250

Key challenges:
Parkinson's disease, stroke, multiple sclerosis, autism, Alzheimer's disease, ischemic stroke, epilepsy, cognition, depression, neuroinflammation, inflammation, neurodegeneration, dementia, aging

Key technologies:
EEG, AI-based (machine learning, deep learning), MRI

Notable technologies:
TMS, functional connectivity, ERP, neuromodulation, meta-analysis, rehabilitation, deep brain stimulation, gait, balance, electromyography, brain-computer interface

Figure 5. Results of bibliometric analyses in D4 Neuromorphic Control/Neurorobotics in the Neuroscience subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 30 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key challenges as well as key and notable technologies.

(II) Dimension 5: Neuroinformatics

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

Keywords utilized *meta-analysis, MRI, deep learning, machine learning, systematic review, ANN, covıd-19, CNN, modelling, image processing, prognosis, neural network, biomarker, stroke, case report, heart failure, visualization, artificial intelligence, children, IoT, fMRI, optimization, depression, survival, pet, image segmentation, feature extraction, imaging, genetic algorithm, computational modeling, breast cancer, segmentation, simulation, classification, diagnosis, CFD, sars-cov-2, task analysis, mortality, Alzheimer's disease, prostate cancer, risk factor, hepatocellular carcinoma, cancer, neuroimaging, computer vision, transformer, multiple sclerosis, pediatric, numerical modelling, finite element analysis, radiomics, immunotherapy, training, mathematical modeling, surgery, gan, additive manufacturing, epidemiology, obesity, blockchain, outcome, inflammation, transfer learning, exercise, ischemic stroke,*

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treatment, deep neural network, ultrasound, functional connectivity, attention mechanism, pregnancy, svm, cognition, network meta-analysis, numerical simulation, LSTM, virtual reality, radiotherapy quality of life, prevalence, mental health, object detection, natural language processing, epilepsy, prediction model, anxiety.

Documents by subject area The search resulted in 788,205 documents; the distribution of which with respect to the subject areas is shown in Figure 6. The most prominent subject area is **Engineering** which contains 119,019 documents that account for 15.1% of the overall number of documents. **Medicine** ranks second with 117,320 documents, whereas **Computer Science** (99,476 documents) and **Neuroscience** (21,468 documents) are the third and the fourth most prominent subject areas, respectively.

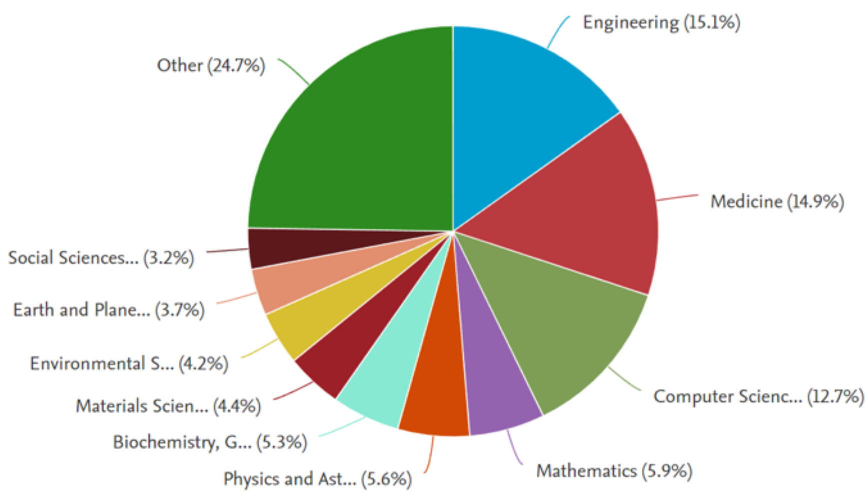

Figure 6. Pie chart illustrating the percentage weight of subject areas in the field of Neuroinformatics.

Remarkably, for the neurotechnology dimension Neuroinformatics, **Engineering** (Figure 7) and **Computer Science** (Figure 8) are technology **exclusive** subject areas (and not technology dominant ones since other than Covid-19 no challenge occurs in the most studied 30 keywords). AI-based technologies (deep learning, machine learning, artificial neural networks, convolutional neural networks, neural networks, artificial intelligence, training, feature extraction), modeling techniques (finite element modeling, mathematical modeling, computational modeling, simulation, computational fluid dynamics), imaging technologies (image processing, visualization, image segmentation, MRI, computer vision), and Internet of Things (IoT) comprise key and notable technologies. Being technology exclusive subject areas, there are no key challenges studied in these subject areas. Notable challenges include sustainability, climate change, energy efficiency, and lithium-ion batteries for Engineering and security, privacy, brain tumors, uncertainty, natural language processing, and social media for Computer Science. **However, such R&I dedicated to challenges comprise only a small portion of the R&I done in those subject areas strongly suggesting that for the Neuroinformatics dimension, the technology development investments made**

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(funds and engagement of experts) do not correlate with the challenges. Technology development predominantly for the sake of technology development, e.g., to be used later in presently unforeseeable solutions to challenges, is an effort to be sustained. Yet, as long as developed technologies do not aim at providing solutions to certain challenges, neither their translational innovation perspectives can be built nor will their impact on society be identifiable.

In contrast, **Medicine** (Figure 9) is a technology and challenge mixed subject area. The key challenges studied in this area are stroke, children, depression, cancer (breast cancer, prostate cancer, hepatocellular carcinoma) mortality, Alzheimer's disease, risk factor, multiple sclerosis, and pediatric. The key technologies include bibliometric techniques (meta-analysis, systematic review, case report), medical imaging technologies (MRI, computed tomography, neuroimaging, radiomics, fMRI), AI-based technologies (deep learning, machine learning, artificial intelligence), prognosis, and biomarker. Although the research is limited exclusively to further characterization of challenges and despite challenges studied in conjunction with potential solution-providing technologies requiring further bibliometric analyses, the Medicine subject area appears to show a balanced relationship between challenges and technology development. Also, the translational innovation potential is not visible from Figures 7–9 and needs to be studied in further detail. **Nevertheless, the need for a transdisciplinary collaboration between Engineering, Computer Science, and Medicine subject areas is clearly apparent to make an impact on the industry and economy. The link to societal challenges and impact would remain lacking though for which dedicated other analyses need to be conducted.**

Neuroscience (Figure 10) is a challenge dominant subject area. The key challenges studied in the Neuroscience subject area include Alzheimer's disease, stroke, multiple sclerosis, Parkinson's disease, cognition, depression, epilepsy, schizophrenia, dementia, aging, autism, cognitive impairment, and ischemic stroke. The key technologies studied are medical imaging technologies (MRI, fMRI, functional connectivity, neuroimaging, diffusion tensor imaging, EEG), meta-analysis, biomarker and AI-based technologies (machine learning, deep learning). Notable technologies include rehabilitation, neuromodulation, and decision-making, which can also be considered as a challenge or, broadly, the general aim of typical neurotechnology R&I. Again, it is important to note that the Neuroscience subject area comprises only a small portion of the globally conducted research in the dimension Neuroinformatics but appears key to health- and health care-oriented R&I. **Yet, the translational innovation aspect is unclear and the bibliometric data are still incapable of indicating if the solutions developed will be the ones which society needs.**

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Engineering (119,019 documents, 62,764 author keywords)

A technology exclusive subject area

The most occurring keyword is **deep learning**

Technology/Challenge	Occurrences
deep learning	4834
machine learning	4235
ANN	3594
modelling	2423
CNN	2399
image processing	1954
finite element modelling	1828
neural network	1681
mathematical modelling	1270
optimization	1264
artificial intelligence	1111
simulation	1058
CFD	969
feature extraction	929
visualization	855
IoT	844
image segmentation	830
computational modeling	787
numerical modelling	780
finite element analysis	778
covid-19	761
classification	754
MRI	722
additive manufacturing	708
segmentation	641
computer vision	616
numerical simulation	609
SVM	567
prediction model	554

Key technologies:
AI-based (deep learning, machine learning, ANN, CNN, NN, artificial intelligence, feature extraction), modeling, image processing, finite element modeling, mathematical modeling, optimization, simulation, CFD

Notable technologies:
Visualization, IoT, image segmentation, MRI, computer vision

Key challenges:
None

Notable challenges:
Sustainability, climate change, energy efficiency, lithium-ion battery

Figure 7. Results of bibliometric analyses in D5 Neuroinformatics in the Engineering subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 30 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies, and notable challenges. **Key challenges are lacking in this technology exclusive subject area**.

Medicine (117, 320 documents, 81,916 author keywords)

A technology and challenge mixed subject area

The most occurring keyword is **meta-analysis**

Technology/Challenge	Occurrences
meta-analysis	7942
MRI	6647
systematic review	3902
covid-19	3217
deep learning	2334
machine learning	2233
prognosis	1890
biomarker	1409
stroke	1409
case report	1395
children	1314
depression	1140
computed tomography	1138
breast cancer	1071
artificial intelligence	1039
diagnosis	974
sars-cov-2	965
mortality	901
Alzheimer's disease	890
prostate cancer	888
risk factor	836
hepatocellular carcinoma	804
cancer	800
neuroimaging	799
multiple sclerosis	790
pediatric	790
radiomics	762
fMRI	755
immunotherapy	751

Key technologies:
Bibliometric (meta-analysis, systematic review, case report), medical imaging (MRI, computed tomography, neuroimaging, radiomics, fMRI), AI-based (deep learning, machine learning, artificial intelligence), prognosis, biomarker

Notable technologies:
immunotherapy

Key challenges:
Stroke, children, depression, cancer (breast cancer, prostate cancer, hepatocellular carcinoma) mortality, Alzheimer's disease, risk factor, multiple sclerosis, pediatric

Figure 8. Results of bibliometric analyses in D5 Neuroinformatics in the Medicine subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 30 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies as well as key challenges.

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Computer Science (99,476 documents, 66,501 author keywords)

A technology **exclusive** subject area

The most occurring keyword is **deep learning**

Technology/Challenge	Occurrences
deep learning	6377
machine learning	4689
CNN	3177
ANN	2624
image processing	2278
neural network	1881
visualization	1371
artificial intelligence	1355
IoT	1282
modelling	1241
covid-19	1197
image segmentation	1117
feature extraction	1108
computational modeling	1077
segmentation	1071
classification	1035
optimization	947
ontology	941
task analysis	915
MRI	796
computer vision	791
transformer	791
simulation	739
training	727
mathematical modeling	723
GAN	717
blockchain	696
transfer learning	680
deep neural network	650

Key technologies:
AI-based (deep learning, machine learning, CNN, artificial neural network, NN, feature extraction, training), image processing, visualization, modelling, image segmentation, computational modeling

Notable technologies:
Classification, optimization, MRI, computer vision, GAN, block chain

Key challenges:
None

Notable challenges:
Security, privacy, brain tumor, uncertainty, natural language processing, social media

Figure 9. Results of bibliometric analyses in D5 Neuroinformatics in the Computer Science subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 30 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies and notable challenges. **Key challenges are lacking in this technology exclusive subject area**.

Neuroscience (21,468 documents, 20,482 author keywords)

A challenge dominant subject area

Still, the most occurring keyword is **MRI**

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

Key challenges:
Alzheimer's disease, stroke, multiple sclerosis, Parkinson's disease, cognition, depression, epilepsy, schizophrenia, dementia, aging, autism, cognitive impairment, ischemic stroke

Key technologies:
Medical imaging (MRI, fMRI, functional connectivity, neuroimaging, diffusion tensor imaging, EEG), meta-analysis, biomarker, AI-based (machine learning, deep learning)

Notable technologies:
Rehabilitation, neuromodulation, decision making

Figure 10. Results of bibliometric analyses in D4 Neuroinformatics in the Neuroscience subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 30 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key challenges as well as key and notable technologies.

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(III) Smart Cities

The field of Smart Cities utilizes principles of cognition and neuroscience to comprehend and anticipate human behavior and requirements within urban environments. Appropriate solutions can then be devised and implemented via neurotechnologies to enhance the quality of life and well-being for present and future generations. This Smart City vision (Figure 11) positions itself at the nexus of neuroscience/neurotechnology, urban space, and societal interactions. Operationalizing this vision requires a hybrid intelligence-based co-production of knowledge, where education, R&I, and societal innovation should go hand-in-hand. This approach addresses key focus areas in line with several UN Sustainable Development Goals (SDGs), particularly Goal 3 (good health and well-being), Goal 4 (quality education and lifelong learning), Goal 7 (affordable and clean energy), Goal 9 (industry, innovation, and infrastructure), Goal 10 (reduced inequalities), Goal 11 (sustainable cities and communities), Goal 13 (climate action), and Goal 16 (peace, justice, and strong institutions). These goals, in the context of Smart Cities, indicate the need to (1) enhance the health and well-being of individuals residing in cities while ensuring inclusivity in urban life and (2) ensure that urban development and planning contribute positively to resilience and sustainability. The former involves the intelligent design of public spaces, mobility, and transportation, and the latter involves better disaster management, planning of city logistics, and waste management.

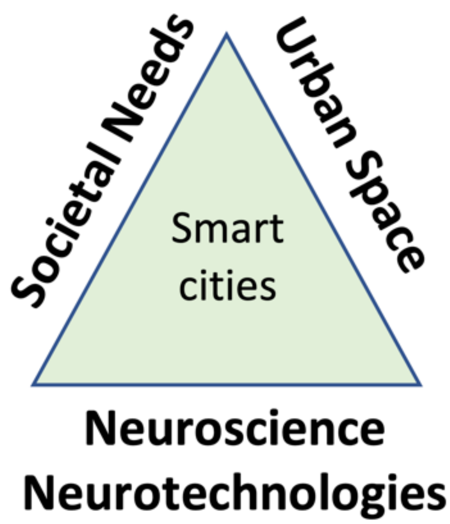

Figure 11. Smart Cities as a hybrid-intelligence concept in the nexus of (i) neuroscience/neurotechnologies, (ii) urban space, and (iii) society.

Broadly, "going smart" while facilitating achievements towards above-mentioned goals also raises significant ethical and privacy concerns that must be carefully managed. Therefore, implementing the Smart City vision mandates a transdisciplinary and integrative approach to address the critical issues and concerns of urban development and planning by allowing the consistent and coherent communication of multiple codes and perspectives (Kourtit and Nijkamp, 2012; Castells, 2000). Needless to say, a strong collaboration among governments, industry, academia, and civil society organizations and purposive

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action is also key (Komninos and Kakderi, 2019; Torbert, 2004). The ultimate goal is not just to improve effectiveness but to ensure that technological advances also serve human well-being and promote healthier and more sustainable urban planning and design purposes (Pykett et al., 2020).

Based on those arguments, we consider Smart Cities an extremely relevant field for the Science with and for Society initiative that can be studied as a neurochallenge and used to provide a unique insight to be incorporated into this deliverable Strategy and Action Plan for Industrial Integration and Cooperation in NeurotechEU. Therefore, motivated by the potential interplay between societal challenges and solution-providing technologies, a bibliometric analysis of the literature on Smart Cities was conducted through the lens of neuroscience and neurotechnology. **However, now equipped with the outcomes of the bibliometric analyses shown above in parts (I) and (II), we were also concerned about a lack or insufficiency of such interplay between challenges and technologies.**

In this section, we provide a comprehensive overview of the research landscape around smart cities using data from the period 2018–2022 extracted from the Scopus database, based on a list of terms and themes identified within the scientific community, to address the following four research gaps: (1) mapping the knowledge structure in the literature around smart cities and exploring emerging topics in neuroscience and neurotechnology as they apply to smart cities; (2) evaluating to what extent technological solutions and advances effectively address societal and environmental challenges in the 21st century; (3) discussing, using key research streams, how to better create synergies and complementarities to contribute to the overarching goals of health, inclusivity, safety, and resilience in urban development; (4) providing insights for strategic planning and future research directions to policymakers, funding agencies, and institutions.

Keywords Utilized (i) Initially generated list of terms characterizes the scope of Dimension 8, i.e., Neurometaphysics: Neuroaesthetics, Neurolaw, Neurophilosophy, Neuroethics, Mental health, Neuroarchitecture, Neurourbanization, Neuroart, and Neurodesign.

Keywords Utilized (ii) The set of keywords drafted, refined, and augmented through consultation with experts and finalized are: Mobility, Access to public transportation, Micro-mobility problems, Socially inclusiveness, Care solutions, Harmony, Smart design of public space, Frugal Technologies, Resilience, Real-time resilience, Adaptation, Physical and social landscapes, Comfort and well-being, Human-centered design Disaster management, Nudges, Bottom-up governance, Data-based governance, Evidence-based decision-making, Societal innovation, Open-data platforms, Technology as commons, Technological literacy Dissemination, Citizen science Waste management, Classification for recycling, Recycling of plastics, Water management, Sustainability, Resource-aware planning, and Interaction of autonomous vehicles.

The relevance of the bibliometric analysis to Smart City research was ensured by narrowing our search to those papers where the "smart cities/city" keyword appeared, along with terms and themes representing Neuroscience and Neurotechnology in relation to Smart Cities (listed in Keywords Utilized (i)) or terms and themes characterizing a Smart City concept (listed in Keywords Utilized (ii)). When one searches these lists with the concept of a "smart city," the evolution of the idea becomes apparent. It shifts from being primarily about technology to focusing on people, eventually embracing inclusive and participatory governance.

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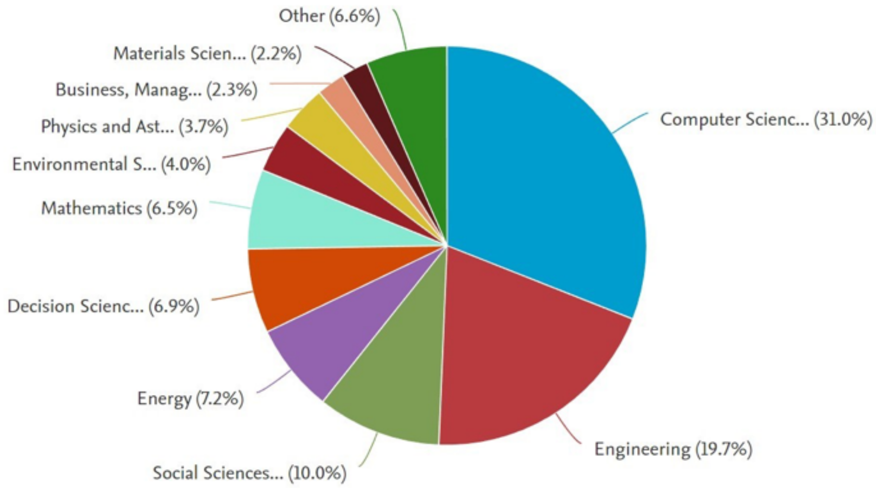

Figure 12. Pie chart illustrating the percentage weight of subject areas in the Smart Cities field.

Documents by Subject Area The search resulted in 27,346 documents. Figure 42 shows the distribution of documents with respect to the subject areas. The most prominent subject area is **Computer Science**, which contains 19,910 documents that account for 31.0% of the overall number of documents. **Engineering** ranks second with 11,893 documents that account for 19.7% of the overall number of documents. **Therefore, half of the global research in the field of Smart Cities is highly technical. Social Sciences** ranks third with 6,138 documents (10% of documents). Due to its high relevance, we also studied **Environmental Sciences** which contains 2,433 documents. **Neuroscience** does not appear to be a field dominating the scene presently (appearing within the group of subject areas referred to as Others) but might become prominent, given its potential for new collaborations with other disciplines.

Computer Science (Figure 13) and **Engineering** (Figure 14) are technology dominant subject areas. Internet of Things (IoT) and AI-based technologies (machine learning, deep learning, artificial intelligence) are key technologies in the field of Smart Cities. Notable technologies for both subject areas are network technologies (blockchain, cloud computing, wireless sensor networks) and sensor technologies. Key challenges for the subject area Computer Science are security, intelligent transportation, and privacy, whereas those for Engineering also include sustainability. Similar to our interpretations in the dimension Neurorobotics, the key technologies, i.e., IoT and AI-based technologies, can be applied for the solution to any challenge and are characteristic technologies for neurotechnology, hence they are relevant for the Smart Cities field as well. The same is valid for sensor technologies since neurotechnology is largely about collection of data and blockchain, cloud computing, wireless sensor networks are also relevant for data collection, storage, transformation, etc. **Therefore, overall, the findings suggest that the most common challenges in the field of Smart Cities and the most common technologies are in concert.** The less common challenges include energy efficiency, governance, smart governance, urban planning, health care, smart contracts, smart meters, smart building, smart home, internet of vehicles, quality of service, resource allocation, architecture, and authentication in the subject area Computer Science and, additionally, energy harvesting, renewable energy, energy management, waste management, resilience, and smart mobility in the subject area of Engineering. These challenges addressed by global R&I are sensible and relevant ones for the field of Smart Cities regarding these two technical subject areas. Yet, one should note that means of data collection other than sensor technologies such as citizen science, security cameras, etc., are plausible but are not included in the studied keywords.

The coherence between challenges and technologies in the subject area Social Sciences (Figure 15) **on the other hand is remarkably and unexpectedly lacking** as, above all, this is also a <u>technology dominant subject area</u>. Key technologies also studied globally in social sciences are identical to those in the technical sciences of Computer Science and Engineering, i.e., IoT and AI-based technologies (machine learning, artificial intelligence, deep learning). Notable technologies, on the other hand, include Information/Network technologies (information & communication, blockchain, cloud computing, GIS). Key challenges also directly overlap with those studied in Computer Science and Engineering subject areas to include sustainability, intelligent transportation, urban planning, governance, privacy, and security. The same applies for the notable challenges, which include those listed above for Computer Science and Engineering. The curious question here, which requires a more detailed assessment (i.e., studying individual documents for a more specific understanding) is if the outcomes of the most studied three subject areas actually support the hybrid intelligence-based co-production of knowledge, as indicated in the problem description above. Or is it a technology dominant approach conducted by technical R&I experts, which are also published in social sciences journals?

Subject Area: Computer Science (19,910 documents , 38,189 (6584 smart city) author keywords)

A <u>technology</u> dominant subject area
The most occurring keyword is **IoT**

Technology/Challenge	Occurrences
internet of things	3959
machine learning	1851
deep learning	693
blockchain	645
cloud computing	581
security	542
intelligent transportation systems	533
artificial intelligence	518
edge computing	501
wireless sensor networks	438
privacy preserving	339
fog computing	303
sensors	298
convolutional neural network	292
vehicular ad hoc network	283

Key technologies:
- IoT, AI-based (machine learning, deep learning, artificial intelligence)

Notable technologies:
- Network technologies (blockchain, cloud computing, wireless sensor networks)
- Sensor technologies

Key challenges:
- Security, intelligent transportation, privacy

Figure 13. Results of bibliometric analyses in Neurochallenge Smart Cities in the Computer Science subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 15 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies as well as key challenges.

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Subject Area: Engineering (11,893 documents, 24,695 (3957 smart city) author keywords)

A technology dominant subject area

The most occurring keyword is **IoT**

Technology/Challenge	Occurrences
internet of things	2337
machine learning	1010
deep learning	355
blockchain	348
artificial intelligence	319
intelligent transportation systems	316
security	312
cloud computing	308
wireless sensor networks	286
edge computing	247
sensors	222
smart grid	219
sustainability	185
privacy preserving	176
vehicular ad hoc network	166

Key technologies:

- IoT, AI-based (machine learning, deep learning, artificial intelligence

Notable technologies:

- Network technologies (blockchain, cloud computing, wireless sensor networks)

- Sensor technologies

Key challenges:

- Intelligent transportation, security, sustainability, privacy

Figure 14. Results of bibliometric analyses in Neurochallenge Smart Cities in the Engineering subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 15 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies as well as key challenges.

Subject Area: Social Sciences (6,138 documents, 15,693 (2364 smart city) author keywords)

A technology dominant subject area

The most occurring keyword is IoT

Technologies/Challenges	Occurrences
internet of things	575
machine learning	498
sustainability	191
information and communication technology	130
blockchain	125
artificial intelligence	116
intelligent transportation systems	112
deep learning	110
urban planning	95
cloud computing	82
governance	84
privacy preserving	81
security	80
geographic information system	72
smart grid	69

Key technologies:

- IoT, AI-based (machine learning, artificial intelligence, deep learning

Notable technologies:

- Information/Network technologies (information & communication, blockchain, cloud computing, GIS)

Key challenges:

- Sustainability, intelligent transportation, urban planning, governance, privacy, security

Figure 15. Results of bibliometric analyses in Neurochallenge Smart Cities in the Social Sciences subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 15 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies as well as key challenges.

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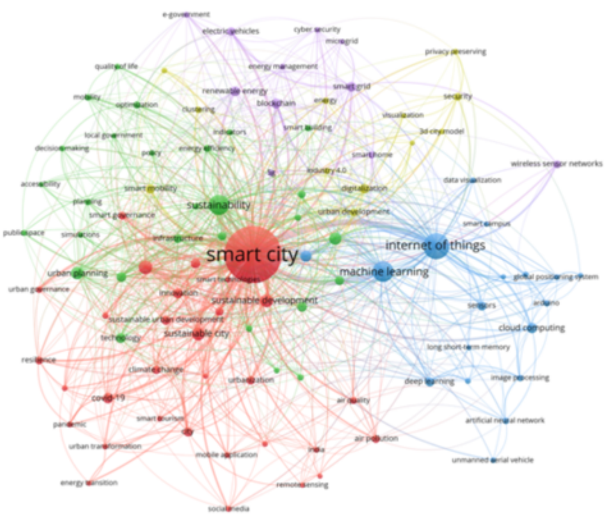
Subject Area: Environmental Sciences (2,433 documents, 6,288 (862 smart city) author keywords)



A technology dominant subject area
The most occurring keyword is **IoT**

Technologies/Challenges	Occurrences
internet of things	183
machine learning	118
sustainability	113
information and communication technology	53
sustainable development	47
sustainable city	45
artificial intelligence	40
intelligent transportation systems	35
cloud computing	29
governance	28
renewable energy	28
smart grid	28
geographic information system	27
innovation	27
sustainable smart city	27

Key technologies:
- IoT, AI-based (machine learning, artificial intelligence)

Notable technologies:
- Information/Network technologies (information & communication, cloud computing, smart grid, GIS)

Key challenges:
- Sustainability, sustainable development, sustainable city, intelligent transportation, governance, renewable energy

Figure 16. Results of bibliometric analyses in Neurochallenge Smart Cities in the Environmental Sciences subject area. Left panel: Keyword co-occurrence network based on author keywords. Mid-panel: Tabulated most occurring 15 keywords showing technologies (green font) and challenges (purple font). Right Panel: A summary of findings showing key and notable technologies as well as key challenges.

The answer may come from the **Environmental Sciences** (Figure 16) subject area, which is also a technology dominant subject area with the key technologies, notable technologies, and key challenges almost entirely overlapping with those presented above. This may suggest that the response to the latter question may be yes! **It is suggested that hybrid intelligence-based co-production of knowledge where education, R&I, and societal innovation go hand-in-hand requires a first-hand understanding of Societal Challenges from the direct source, i.e., society.** A novel approach has been developed by NeurotechEU, which is summarized in the following section.

Understanding Societal Challenges Survey

Rationale

Academic bodies with the perspective of characterizing the university of the future, like NeurotechEU, and the technological innovations they provide will shape and serve society but will also require support from society. Trust in and thus acceptance of new technologies will determine consumer reach. Public opinion also influences policymaking, where salient topics with coherent opinions about them are more likely to become integrated into programmatic priorities (Burstein, 2003; Christian, 2008; Spendzharova and Versluis, 2013; Bromley-Trujillo and Karch, 2021). However, there seems to be a gap between science and the public (McFadden, 2016; Coates McCall et al., 2019). While neuroscientists, neuro-engineers, and other innovators interact with government agencies to secure funding for research and exchange ideas with each other, they typically do not reach out to the public to decide on the technologies they wish to

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develop (Figure 17). Even engineers and clinicians, who develop and apply the technologies, respectively, do not communicate enough (Weber, 2019). In the meantime, public opinion is shaped through the media. Policymakers themselves shape public opinion, but many other influences exist, including misinformation (fake news) spread online (Funk, 2020; Cacciatore, 2021). Therefore, it is important that scientists, too, connect with the public, understand their challenges, and integrate this knowledge into the scientific process.

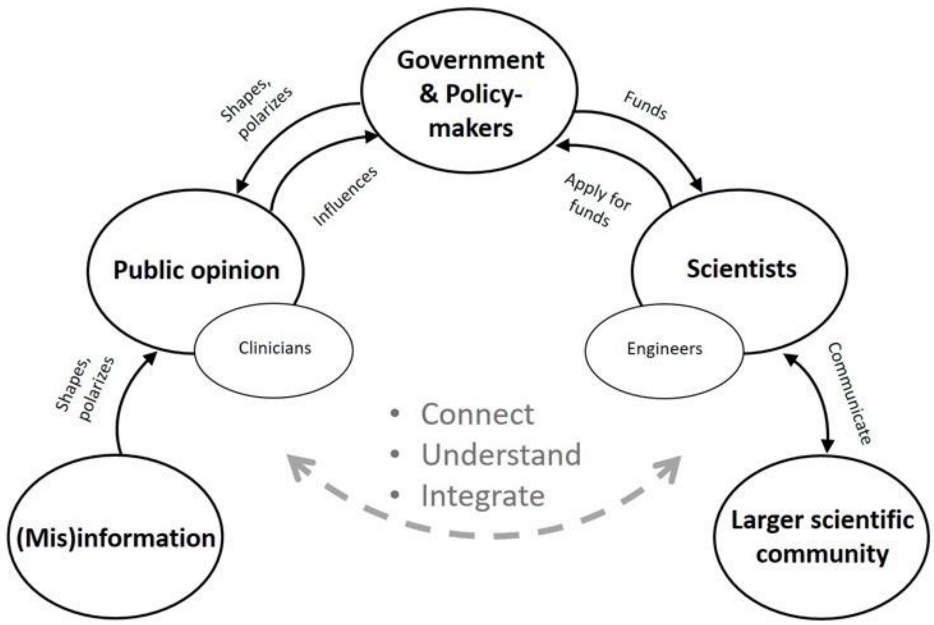

Figure 17. The scientist's web. Neuro-engineers and other innovators typically interact with government agencies to secure funding for research. They submit research proposals in response to specific calls that are based on programmatic priorities. Scientists also interact with each other to exchange ideas, for example, at scientific venues. Communication with the public is rare, however. Even engineers who develop the technologies and clinicians who apply them do not communicate enough (Weber, 2019). In the meantime, public opinion is shaped through public media, including misinformation spread online.

Evidence suggests that the level at which the general public and patients, in particular, accept and welcome new neuro-technologies is variable. Sattler and Pietralla (2022) found, for example, that the moral acceptability rate and willingness to use brain stimulation devices were 25.5% and 28.7%, respectively, indicating that the majority of the participants – a representative sample of the adult German population – is not fully embracing this technology. The results were similar for brain-computer interfaces, the second type of technology examined. The use of these technologies for treatment was deemed more acceptable than their use for self-enhancement, and noninvasive applications were preferred over invasive ones. Sociodemographic characteristics, specifically, being female, older, and religious also contributed to a lower acceptance rate and/or willingness to use one or both technologies (Sattler and Pietralla, 2022). A US-based survey found that the public was much more worried than enthusiastic about gene editing, brain chips, and synthetic blood used for self-enhancement (Funk et al., 2016). While the

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interest in using assistive technologies was high in patients with spinal cord injuries, the acceptability rate of invasive technologies was still less than 50% (Huggins et al., 2015).

Thus, healthy people as well as patients clearly prefer non-invasive over invasive neuro-technologies. Surprisingly, however, it is common that neuroscientists and neuro-engineers develop cutting-edge technologies that are highly invasive but considered the next frontier, and then face a myriad of challenges in translation (Weber, 2019; Shen et al., 2020). That said, even non-invasive technologies have their barriers in actually getting used; patients with Parkinson's disease reported a low usability, discomfort, or pain, and a lack of familiarity with such technologies (Laar et al., 2023). Also, despite their great potential, neuro-technologies used in preventive medicine have received much less attention than technologies that treat symptomatology (Elenko et al., 2015). Neuro-technologies that focus, for example, on sleep, diet, exercise, and cognitive biases, which are often impacted early in the development of psychiatric and neurological diseases, might help prevent the transition from these early changes into full-blown conditions that are hard to treat by the time clinical diagnoses are made (Schulz, 2020). Therefore, NeurotechEU has a great opportunity to set its mark as a leader in the advancement of neuro-technologies that take attitudes of people into account and focus on prevention and health in addition to (or more than) disease and treatment.

NeurotechEU will be confronted with many different attitudes about what neuro-technological advances should entail. Somewhat representative of the complexity that makes up the European Union (EU) and its Associated Member States (AC), our member countries – The Netherlands (NL), Spain (ES), Sweden (SE), Germany (DE), Türkiye (TR), Romania (RO), Hungary (HU), France (FR), and Iceland (IS) who are represented by Radboud University, Miguel Hernández University of Elche, Karolinska Institutet, University of Bonn, Boğaziçi University, Iuliu Hatieganu University of Medicine and Pharmacy, University of Debrecen, University of Lille, and Reykjavik University, respectively – differ in social, cultural, and individual characteristics that may translate into differences in opinion, both at the expert level and our broader societies. To serve everyone in the best way possible, we therefore plan to conduct a transnational survey with the goal of better understanding the challenges of our nations. We aim to compare and contrast our nations specifically with respect to their perspectives on neuro-technological advances, that is, their needs for, interests in, access to, knowledge of, and trust in neuro-technologies, and whether these should be regulated. We further aim to determine the socio-demographic and personality characteristics that best predict positive and negative attitudes about neuro-technological advances. To our knowledge, no other transnational study has examined these variables before. We expect that, in the short-term, our study will provide a deeper understanding of the challenges that our nations are facing, the similarities and differences between our countries, and that through the process of socially engaged science we will integrate our countries more. In the long run, we hope that our insights will benefit NeurotechEU in its efforts to develop neuro-technologies that people really care about, are accessible, useful, trusted, ethical, regulated, safe, research-based, new and proven, and are actually understood by the user. Connecting with the public, understanding their challenges, and integrating this knowledge into the scientific process may also result in a greater sense of inclusion and more excitement about the opportunities that come with research and innovation (see Figure 18 for a schematic illustrating the complementarity, hence significance of *Understanding Societal Challenges Questionnaire -USCQ* for

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all NeurotechEU domain of actions, and Figure 19 for the coverage of *Understanding Societal Characteristics Form -USCF*).

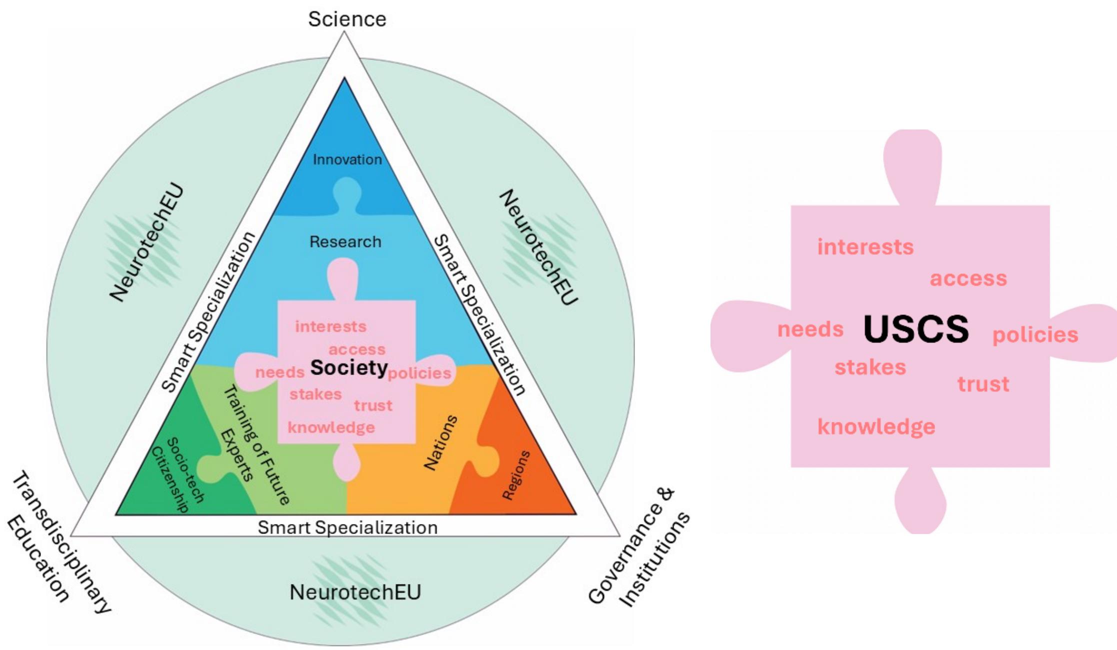

Figure 18. A schematic illustrating how USCS complements all NeurotechEU domains along the lines of NeurotechEU's Smart Specialization based policy and strategy development actions. These domains do concern Education, Research, Innovation, Nations and Regions. Note that there is a special focus on Socio-technological Citizenship, which is a comprehensive education concept WP4 develops to first equip experts that are currently in action, with broader socio-technological citizenship skill sets (e.g., via Lifelong Learning programs) and in time to train the future neurotechnology experts in a transdisciplinary approach.

Achievements

The study protocol of our planned survey was recently published at

- Schulz, D., Lillo-Navarro, C., Slors, M., Hrabeczy, A., Reuter, M. (2024). Understanding societal challenges: a NeurotechEU perspective. *Frontiers in Neuroscience*, *18*, 1330470. doi: 10.3389/fnins.2024.1330470

As described in the publication, we developed the *Understanding Societal Challenges Questionnaire (USCQ)* to assess people's perspectives on neuro-technologies, specifically their needs for, interest in, access to, knowledge of, and trust in neuro-technologies, and whether these should be regulated (Schulz et al., 2024). The USCQ has 30 items and a fixed format that uses Likert scales for most items. It asks the respondents to rate their perspectives on neuro-technological advances more broadly, unlike other questionnaires which focus on a few specific technologies (e.g., Funk et al., 2016; Sattler and Pietralla, 2022). Because neuro-technologies are very diverse, and we are interested in measuring general attitudes of acceptability, it is our intention to not bias the respondents towards a specific topic. We hypothesize that the structure of the USCQ is formed by six latent variables that correlate predominantly with the respective items in the six question domains (needs, interest, access, knowledge, trust, policymaking), irrespective of the NeurotechEU nation that is measured. On the other hand, we expect that the domain means will vary across nations based on differing sociodemographic characteristics. For example, older age groups often feel barriers to the use of new technologies and are less accepting of these (Tacken et al., 2005; Sattler and Pietralla, 2022), and among our member countries, DE is the oldest with a median age of 44.91, whereas TR is the youngest with a median age of 31.76 (https://database.earth/population/median-age). By this criterion, TR is expected to have higher acceptability rates than DE. The link between religiosity and societal perspectives on neuro-technological advances is also expected to impact our research, as it was shown that people who identify as religious are less accepting of new neuro-technologies (Funk et al., 2016; Sattler and Pietralla, 2022). According to the Inglehart-Welzel World Cultural Map, TR and RO have relatively high scores on the traditional and survival dimensions which emphasize the importance of religion and economic and physical security, respectively, whereas countries like DE, NL, and IS fall at the opposite side of the spectrum with high scores on the secular-rational and self-expression dimensions, and HU, ES, and FR falling somewhere in between (World Values Survey 7, 2023). On the other hand, countries that score high on the survival dimension like TR and RO report relatively poor health and high levels of trust in science and technology, which might make neuro-technological advances more acceptable.

We further developed the *Understanding Societal Characteristics Form (USCF)* to identify the sociodemographic variables that best predict positive and negative attitudes about neuro-technological advances (Schulz et al., 2024). The USCF has 20 items (Figure 19) that ask about age, gender, education, size of the residential area, religiosity, political standings, and more. It was designed for administration across EU/AC countries and is therefore taking the diverse educational systems, cultural norms, and sensitivities of our nations into account.

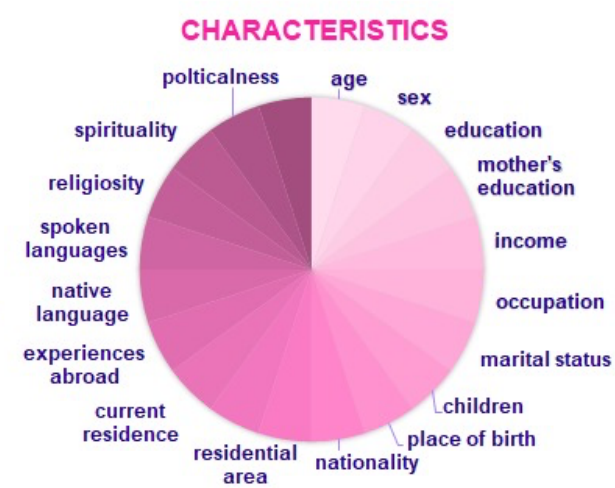

Figure 19. The USCF asks about 20 characteristics related to age, gender, education, size of the residential area, religiosity, political standings, and more.

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Action plan (short-term)

In the short-term, our goal is to better understand the challenges of our NeurotechEU nations, specifically, their needs for, interests in, access to, knowledge of, and trust in neuro-technologies, and whether these should be regulated. The data collected in each participating country will be used to determine the similarities and differences between our nations, and the characteristics that best predict positive and negative attitudes about neuro-technological advances.

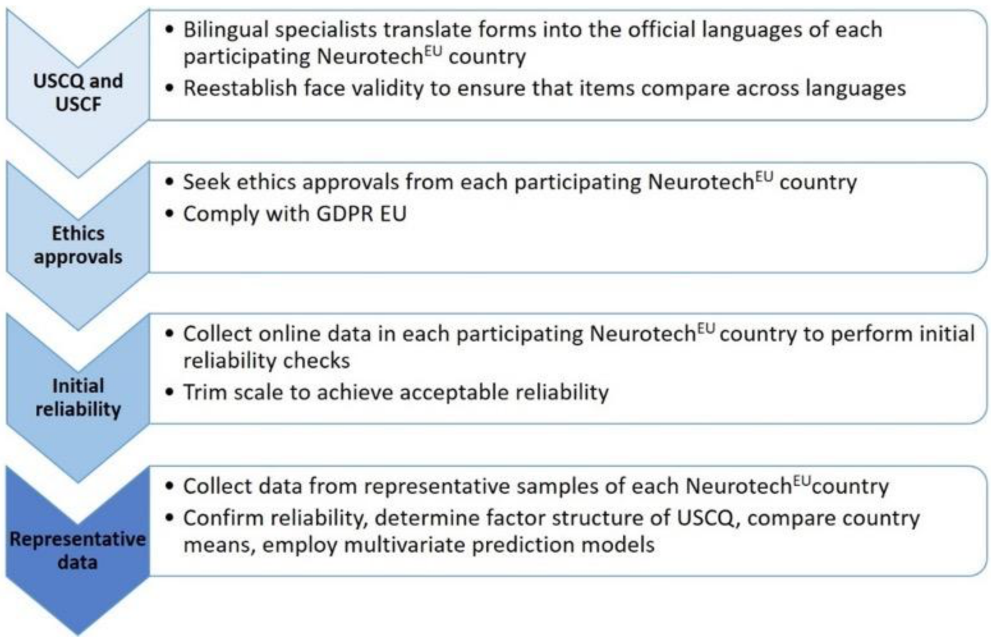

Figure 20. Study design. The progression of steps to be implemented next in project "Understanding Societal Challenges: A NeurotechEU perspective." GDPR EU = General Data Protection Regulation EU (2016/679).

While we have established face validity of the USCQ and USCF in the English language, these will be translated into the official languages of each participating NeurotechEU country. Translations into Turkish, Dutch, Spanish, French, and German have already been made. Next, ethics approvals will be sought by each participating country. The translated forms will then be administered online to 100 participants per nation for initial reliability testing of conceptually similar items. The scales will be trimmed, if necessary, to achieve acceptable reliability (Cronbach's alpha > 0.70). Finally, we will collect data from a representative sample of each country. Based on other nationwide surveys, we predict that ~1000 data per nation will suffice to achieve representation (3M State of Science Index, 2022). While this is difficult to achieve, we will seek support from research companies specialized in collecting such data. We are currently exploring a testing scheme via a professional research company with a worldwide network. The participants will be found in their day-to-day environments, both online and in the field, as appropriate. National statistics will be used to determine the proportion of internet users and non-users, age distributions, and other socio-demographic characteristics of each sample. We will further classify our respondents into different stakeholder categories, such as patients, caregivers, clinicians, and company representatives, who would most directly benefit from neuro-technological advances. Participants who cannot understand the questions due to cognitive impairments will be excluded from analysis. Caregivers (and researchers) can read the questions and record the answers for another person, if deemed necessary, for example due to sensory-motor impairments. Random-sampling procedures will be used for recruitment. Once we have collected the final data, the reliability analyses will be repeated, the factor structures of the USCQ determined using confirmatory factor analysis (CFA) in a structural equation model framework, country means compared, and the influence of population characteristics on attitudes regarding neuro-technological advances assessed using simple correlation and multi-factorial analyses. The results will be disseminated to the NeurotechEU community and beyond. The design of our study is summarized in Figure 20.

Action plan (long-term)

In the long run, the insights gained will benefit NeurotechEU in its efforts to develop neuro-technologies that people really care about, are accessible and understood by the user, are ethical, regulated and safe, based on research, and are new and clinically proven.

In conclusion, our attempt to bridge the gap between science and the public may result in neuro-technological advances that our broader societies will value more. We further expect to highlight the importance of non-invasive over invasive neuro-technologies, and technologies used in preventive medicine over those used to treat symptomatology, both in education and the translation of scientific progress into industrial products.

Smart Specialization Strategy

In this section, we briefly explore the Smart Specialization Strategy (S3) concept to situate our strategy and action plan for Cooperation models including the sustainable regional development from theoretical and methodological perspectives. We then explain in more detail the deliberative policy framework we have within NeurotechEU, centered around neuroscience and neurotechnology.

As is well-known, the Smart Specialization Strategy (S3), introduced as part of the EU's Cohesion Policy during the 2014–2020 period, marked a significant shift from traditional research and innovation policies. Instead of applying a broad, one-size-fits-all approach across various sectors and regions, Smart Specialization focuses on identifying a region's unique strengths, assets, and competitive advantages (Foray et al., 2018). This strategy encourages regions to prioritize and invest in areas of expertise where they can have the greatest impact, thereby fostering innovation deeply rooted in local contexts and needs. By leveraging regional strengths and resources, Smart Specialization enhances the efficiency and effectiveness of public investments and promotes inclusive and sustainable development tailored to each region's specific characteristics and opportunities. Overall, the approach aims to ensure that innovation efforts are strategically aligned with regional development goals, considering local needs and societal challenges in a manner that also advances the UN Sustainable Development Goals (SDGs).

Throughout the years, S3 has evolved into a well-established field within regional development and innovation studies, supported by a robust and growing body of literature (see Figure 21 for exemplary documents). This literature encompasses a broad range of topics, from the theoretical foundations of S3 (Foray et al., 2018) to practical case studies of its implementation across various regions within the European Union (see, e.g., Paliokaitė et al., 2015). There is also a significant focus on the challenges and best practices associated with S3 implementation, offering valuable insights for policymakers and practitioners alike (Gianelle et al., 2016; OECD, 2013).

Figure 21. Smart Specialization Strategy documents exemplified.

Implementing a Smart Specialization Strategy (S3) involves a series of phases (as depicted in Figure 22), beginning with a deep understanding of the regional context and followed by evidence-based priority setting. This process entails identifying key areas of specialization via a thorough SWOT analysis, which examines the strengths, weaknesses, opportunities, and threats specific to the regions involved, along with stakeholder engagement. Crucially, this approach requires the creation of an innovation ecosystem that integrates public-private partnerships and interdisciplinary programs, fostering close collaboration among various stakeholders, including educational and research institutions, industries, public bodies, municipalities, regional development agencies, and NGOs. This framework aligns with the concept of knowledge and technology “co-production,” which aims to create an “extended peer community” of stakeholders. These stakeholders are not merely considered affected user groups but are recognized as experts, practitioners, and knowledge generators in their own right. Overall, what is proposed here is a pluralistic, participatory, and democratic view of the knowledge and judgment base for policy actions.

It is believed that by aligning such deliberative processes with strategic investments and continuous policy support, regions can become more innovative and competitive and generate contextually relevant economic and societal benefits. Ultimately, the goal is to translate scientific advances into societal benefits aligned with sustainable regional development objectives. As formulated by Funtowicz and Ravetz (1990, 1994), when science is deployed in business strategy and public policy contexts, in many instances, facts are uncertain, values are in dispute, stakes are high, and decisions are urgent. Therefore, the success of S3 ultimately hinges on the quality and transparency of the deliberative institutions and processes and the effective implementation of transdisciplinarity, in line with the Science with and for Society vision where knowledge and expertise are distributed among peer communities rather than hierarchically organized.

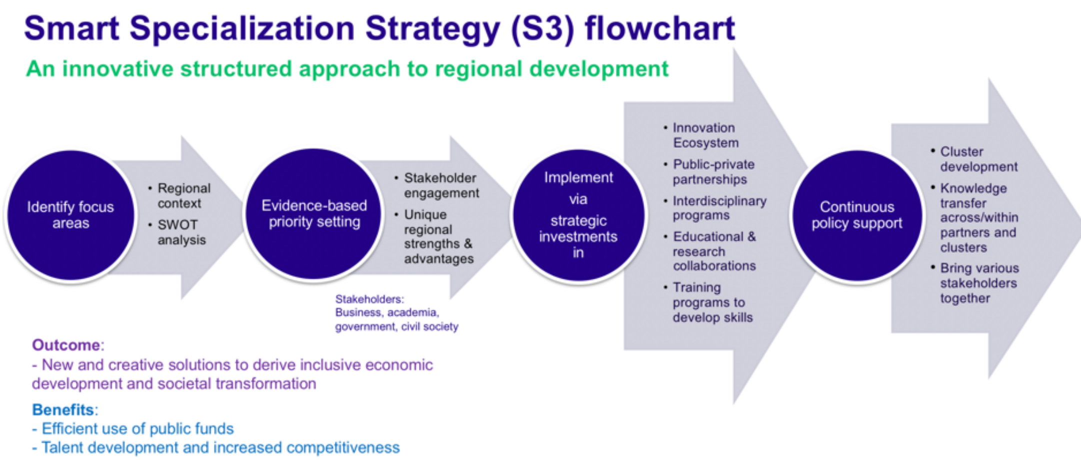

Figure 22. Smart Specialization Strategy explained in a stepwise flowchart.

What specific steps are involved in implementing this S3 framework within the NeurotechEU context? The next section aims at contributing to this task.

Action Plan – Operationalization of the Smart Specialization Strategy (S3) within NeurotechEU

To effectively integrate the material presented so far and operationalize the Smart Specialization Strategy (S3) within NeurotechEU, we start by grounding our approach in a thorough understanding of the regional context.

Phase 1: Engaging with regional context and identifying key stakeholders

Building on the Understanding Societal Challenges Survey detailed above, this initial phase involves, as depicted in Figure 23, from steps (1) to (4), understanding the institutional setting and identifying key stakeholders who play a crucial role in regional development. As partnering universities, we aim to create a comprehensive database of stakeholders and engage with them through knowledge platforms to gather insights and secure support while conducting a comprehensive SWOT analysis of our regions. We believe that only by closely collaborating with these entities and fully grasping regional characteristics and nuances can we adequately identify focus areas that align with each region's unique advantages and the broader goals of NeurotechEU. Such stakeholder engagement ensures that the strategies at the end of the process are inclusive and reflect the community's needs and aspirations. Needless to say, to effectively implement S3 within the regions of partnering universities, it is also crucial to characterize any existing S3 implementations or identify the gaps where such strategies are lacking. This involves a thorough assessment of the methods currently used in these regions, as well examining how well they align with the principles of S3.

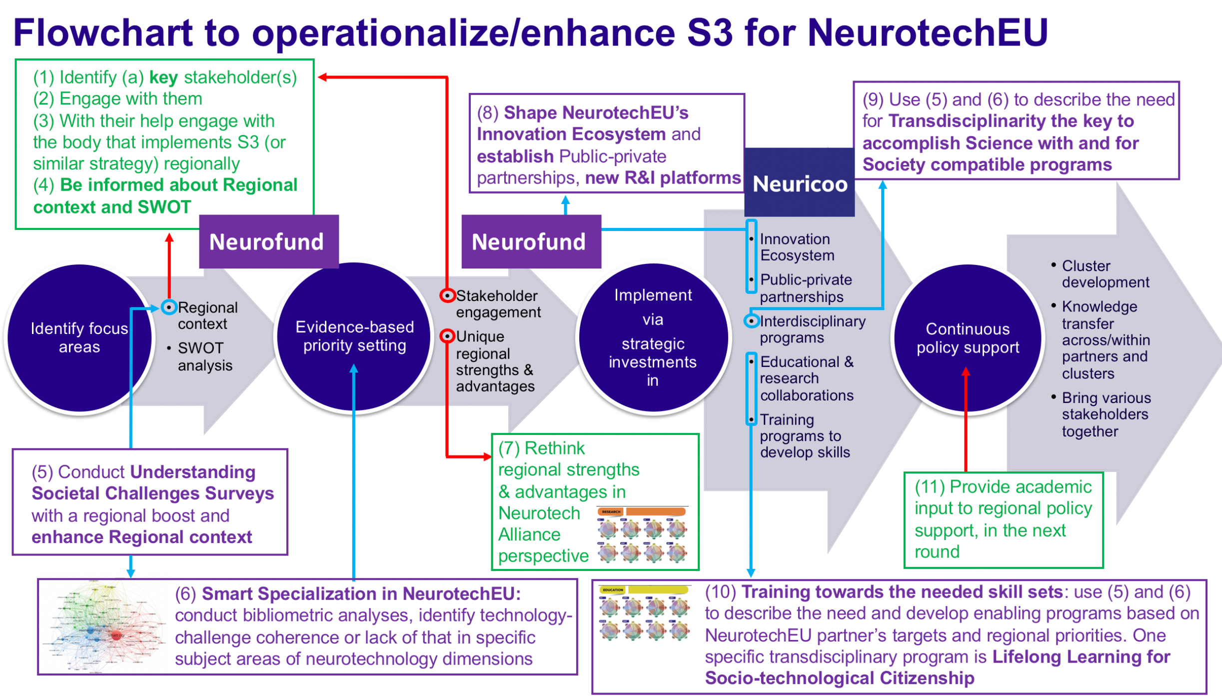

Figure 23. Smart Specialization Strategy in interaction with NeurotechEU's Action Plan for Cooperation models including the sustainable regional development that considers Sustainable Regional Development and Societal Innovation and Impact.

Overall, as depicted in step (5), this initial stage also involves conducting quantitative (e.g., the Understanding Societal Challenges Survey) and qualitative studies (e.g., meetings, workshops, and summits) that enhance our grasp of the regional context and help us decipher the views and positions of multiple actors including key stakeholders in the community in the technology-society nexus. The stakeholders currently identified by each NeurotechEU partner to date are listed in Table 1. Future stages may include further qualitative methodologies including in-depth interviews with community partners, healthcare providers, and individual current and potential users as co-knowledge producers.

Table 1. NeurotechEU Partners and Identified Key and Other Stakeholders

NeurotechEU Partner	Key Stakeholder	Other Stakeholders
STICHTING RADBOUD UNIVERSITEIT (RU)	• Health Valley Netherlands	
UNIVERSIDAD MIGUEL HERNANDEZ DE ELCHE (UMH)		• Hospital Nacional De Paraplejicos (HNP); • Agencia Estatal Consejo Superior De Investigaciones Cientificas (CSIC); • Bit & Brain Technologies Sl (BBTECH); • Ministerio De Universidades (MUNI); • Diputacion Provincial De Alicante (DPA); • Ayuntamiento de Sant Joan d'Alacant (ASJA); • Oficina De Propiedad Intelectual De La Union Europea (EUIPO); • Ayuntamiento De Elche (AYE)
KAROLINSKA INSTITUTET (KI)	• INCF	• Stockholms Universitet (STU); • Kungliga Tekniska Hoegskolan (KTH)
RHEINISCHE FRIEDRICH-WILHELMS-UNIVERSITAT BONN (UBO)	• LIFE AND BRAIN GMBH (LBGMBH) • Transfer Center enaCom (University of Bonn)	• Universitatsklinikum Bonn (UKB); • Deutsches Zentrum Fur Neurodegenerative Erkrankungen Ev (DZNE); • Max Planck Institute for Neurobiology of Behavior - caesar (MPINB); • Bundesinstitut Fur Arzneimittel Und Medizinprodukte (BfArM)
BOGAZICI UNIVERSITESI (BOUN)	• Marmara Municipalities Union	• Boğaziçi Universitesi Teknoloji Transfer Ofisi Anonim Sirketi (BUTTO);

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	• Neurotechnological Solutions Platform	• Budotek Teknopark; • Istanbul Metropolitan Municipality (IMM); • Sabanci Universitesi (SABANCI); • Bilkent Universitesi Vakif (BBK); • Istanbul Universitesi (IU); • Karel Elektronik Sanayi Ve Ticaret Anonim Sirketi (KAREL); • Interact Medikal Teknolojileri A. S. (InTech); • Istanbul Health Industry Cluster Association (ISHEALTH)
UNIVERSITATEA DE MEDICINA SI FARMACIE IULIU HATIEGANU CLUJ-NAPOCA (UMF)		• Asociatia Transilvania It (TITC); • Spitalul Clinic Judetean De Urgenta Cluj (SCJU CJ); • Fundatia pentru Studiul Nanoneurostiintelor si Neuroregenerarii (RoNeuro); • Ministerul Sanatatii (MINSAN)
UNIVERSITE DE LILLE (ULille)	• Satt Nord (SATT NORD)	• Centrale Lille Institut (CLU); • Centre Hospitalier Regional Et Universitaire De Lille (CHULille); • Institut Mines-Télécom Nord Europe (IMTNE); • Institut Pasteur De Lille Fondation (IPL); • Crous De Lille (CROUS); • Métropole européenne de Lille (MEL); • Region Hauts-De-France (RHF); • Rectorat De L Academie De Lille (RAL);

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		• EURASANTE (EURASANTE); • Institut National De Recherche En Informatique Et Automatique (INRIA); • Centre National De La Recherche Scientifique (CNRS); • Institut National De La Sante Et De La Recherche Medicale
HASKOLINN I REYKJAVIK EHF (HR)		• Landspitali University Hospital (LUH); • Nox Medical EHF (NOXM); • Össur hf (Össur); • Sidekickhealth EHF (SKH)

Phase 2: Identifying focus areas

Using the insights gained from stakeholders and the SWOT analysis, we aim to identify the focus areas in the neuroscience and neurotechnology domains (i.e., dimensions of neurotechnology) that are most relevant to the regions' strengths and needs. In this phase, linking regional context to the scientific state-of-the-art is critical, as it will ensure that the regional strategy is informed by the latest scientific advancements and that policies are developed to translate scientific insights from the lab to industry and urban and rural areas. For NeurotechEU, the surveys, combined with bibliometric analyses that assess the coherence between technology and challenges in specific areas within the neurotechnology domain, as depicted in step (6), will provide a solid foundation for tailoring these focus areas and ensure that these areas are also strategically aligned with regional goals. For the assessment of bibliometric data, a unique NeurotechEU Smart Specialization Question Set (Figure 24) will be utilized.

Phase 3: Evidence-based priority setting

The next phase for NeurotechEU is to set more specific priorities based on select future evidence. This phase ensures that the initiative is grounded in the regions' realities and the expertise of partner universities and that the investments made are again strategically aligned with regional strengths and opportunities. As previously mentioned, at this stage in policy development, it is important to critically evaluate whether innovations proposed under S3 are truly relevant to society and whether the "smart" solutions being pursued are sustainable. This phase also involves rethinking regional strengths and advantages in light of NeurotechEU's broader research perspective, as depicted in step (7), and checking potential knowledge complementarities and any knowledge-transfer opportunities. Additionally, in line with society-oriented research methodologies, a comprehensive evaluation and feedback stage is planned to be administered with stakeholders in order to gage and assess the in-progress acceptance and success of the process. Accordingly, any suggested changes will be made to the following phases based on the assessment received.

Scientific state-of-the-art-Smart Specialization question set:

- Which subject areas (e.g., engineering, computer science, medicine, neuroscience etc.) are key and if they are challenge or technology dominant ones?
- Which challenges (e.g., stroke, depression, Parkinson's disease etc.) and/or technologies (e.g., AI, IoT, sensors, robotics, medical imaging, EEG, battery technologies, biomechanics, nanotechnology, etc.) are the most studied ones per subject area?
- Are the challenges and technologies within a subject area inter-related (technology development towards providing solutions to challenges) or not (technology development for the sake of technology development)?
- Are the less studied technologies insignificant/outdated, or do not receive investments (funds + human capital) while they do bare a potential?
- Can we tackle the technology phenomenon as innovative solution vs. important/impactful solution (many people affected by it)?
- Can combinations of different technologies provide impactful and cost-effective solutions to the challenges?
- Can we define Future Emerging Technologies (high risk-high gain technologies that do not exist, but might be there in the future with impact to the economy and society) and tackle those as NeurotechEU?
- How is technology-challenge relation supporting prevention of challenges?

Figure 24. NeurotechEU's Smart Specialization question set. For the assessment of outcomes of the bibliometric analyses, this question set will be employed as a novel NeurotechEU approach that aims at characterizing the scientific knowhow and current research focus in terms of challenges and solution providing technologies and their interrelationships.

Phase 4: Implementation via strategic investments

Once priorities are set, the strategy moves into the implementation phase, where an innovation ecosystem is created and strategic investments are made in focus areas, as depicted in step (8), that help thoroughly shape the NeurotechEU Innovation Ecosystem. Some strategic public-private partnerships fostering collaboration across sectors within each region, the building of NeurotechEU's interdisciplinary programs, and keeping up the transdisciplinary spirit, as depicted in step (9) to accomplish the Science with and for Society vision are crucial at this stage. Educational and research collaborations, along with lifelong learning and training programs for socio-technological citizenship, are also emphasized to develop the necessary skills within the region, as depicted in step (10). One such initiative, as an example here, would be Boğaziçi University's Neurotechnological Solutions Platform (NTSP in Figure 21) and the establishment of the R&D School, which is initially focusing on research and development in neurotechnology with plans to evolve into a Lifelong Learning program that fosters socio-technological citizenship. This long-term educational initiative is designed to equip individuals with the skills and knowledge necessary to navigate and contribute to the rapidly evolving technological landscape. Furthermore, this transdisciplinary education approach will also incorporate elements of community-engaged learning to further nurture and inspire society-based neurotechnological innovations.

Phase 5: Continuous policy support

The final phase involves continuous policy support to sustain and adapt the strategy over time. Providing academic input to regional policy development, as depicted in step (11), through collaborative meetings and stakeholder summits, where diverse perspectives contribute to the ongoing refinement and implementation of the Smart Specialization Strategy within regions and through NeurotechEU, ensures that the strategy remains relevant and effective as regional and technological landscapes evolve. This ongoing support is vital for maintaining momentum and ensuring that the strategy's benefits are realized in the long term. In this phase, it will also be important to continuously monitor the quality of the processes and fight against any systemic barriers (e.g., limited access to information, technocratic discourse depoliticizing decisions, institutional boundaries, corporate dominance) potentially hindering effective stakeholder participation and knowledge co-production.

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