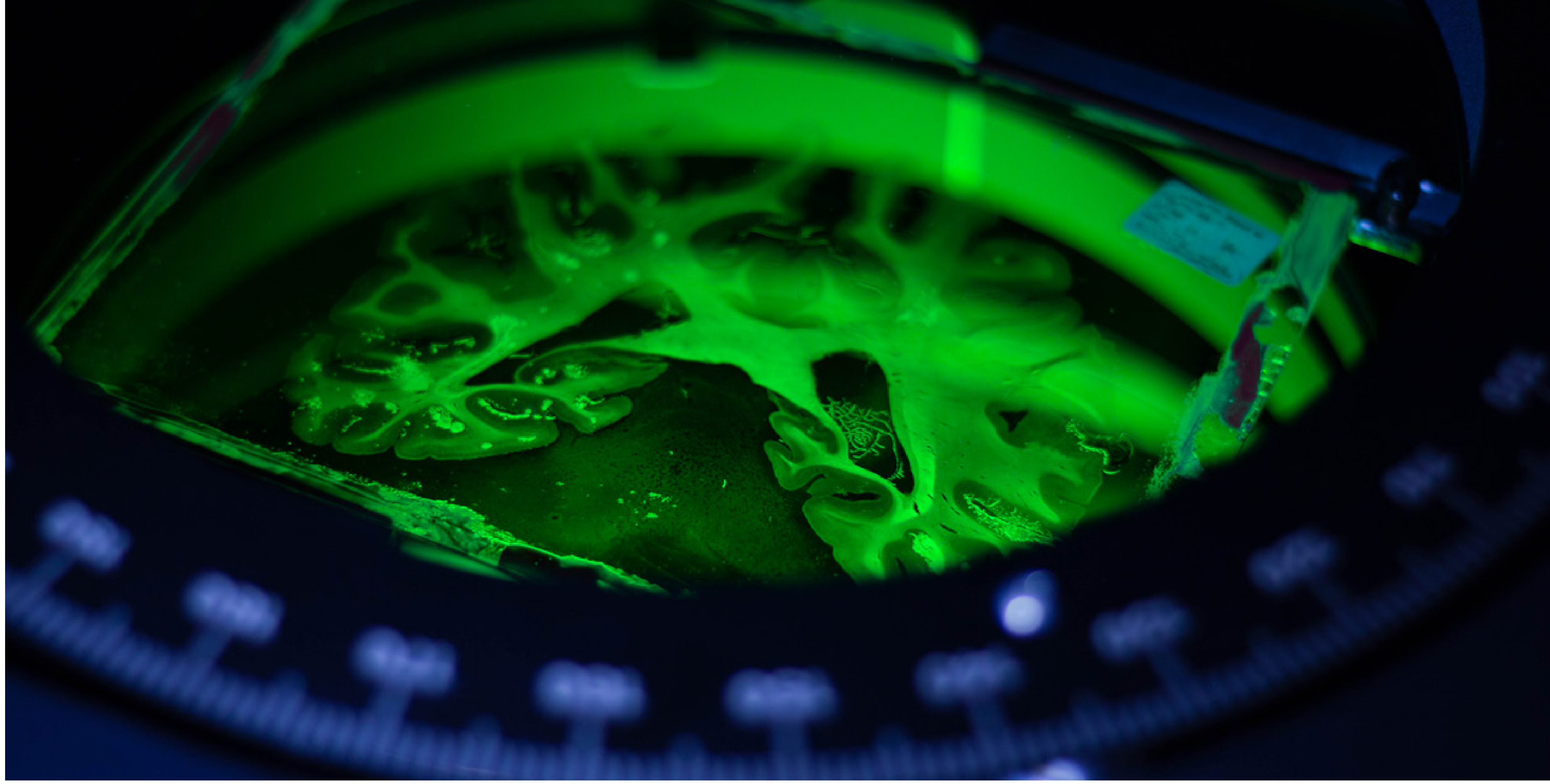
Human Brain Project

Pioneering Digital Neuroscience

How the 10-year Human Brain Project has transformed brain research

Contents

The Human Brain Project: An impactful journey



Brain section being imaged with polarised light.

Since its inception in 2013 as a European Future and Emerging Technologies (FET) Flagship, the Human Brain Project (HBP) has pioneered a new paradigm for brain research at the interface of computing and technology. In 2012, the HBP consortium summarised the goal of the project as follows:

"The Human Brain Project should lay the technical foundations for a new model of ICT-based brain research, driving integration between data and knowledge from different disciplines, and catalysing a community effort to achieve a new understanding of the brain, new treatments for brain disease and new brain-like computing technologies."

Now, after ten years of impactful, intensive, interdisciplinary work by hundreds of researchers across Europe and beyond, the HBP has delivered.

In order to tackle the scientific challenge of understanding an organ as complex as the human brain, experts from different fields have worked together in the HBP in an unprecedently systematic and collaborative way. This has resulted in significant progress in our understanding of human brain structure, function and dysfunction and in new applications in medicine and technology.

These achievements include world-leading 3D atlases of the brain, breakthroughs in personalised brain medicine, and the development of new brain-inspired technologies, e.g., in artificial intelligence and neuromorphic computing. Impressive applications in brain medicine include a visual implant aimed to enable blind people to see and neurostimulation techniques that have already helped paralysed individuals to walk again.

A key outcome and legacy of the HBP is the development of the EBRAINS research infrastructure (RI) – a platform that offers open access to a plethora of advanced digital tools, datasets and services to facilitate brain research. EBRAINS' indispensable role for the brain research landscape has been acknowledged by its inclusion in the ESFRI Roadmap of European research infrastructures in 2021.

EBRAINS software and workflows are tailored for and continuously adapted to the needs of scientists. The quality requirements in terms of the maturity of the technology offered by EBRAINS have been set to a high level and scientific software is accompanied by rich documentation, embedded in analytical pipelines and prepared for use with datasets findable through EBRAINS. The usage of the RI has steadily grown since the launch of the original HBP platform in 2016 and now counts 8,475 returning users from 1,491 different institutions (as of September 2023). To share the tools and workflows with the community at large, HBP research was accompanied by a comprehensive educational programme.

EBRAINS National Nodes are being set up in 11 countries across Europe. They provide their expertise and services to the scientific community through EBRAINS, while also helping to further grow the user base in their country.

A new era for brain research

During the HBP, computing and digitalisation have fundamentally reshaped the way brain research is carried out – a transformation that has been breathtaking in its pace, scale and impact. Supercomputers, big data analytics, simulation, neuromorphic computing, robotics and AI have all become new additions to the toolbox of modern neuroscience. In turn, our improved understanding of the brain is also changing these technologies, from brain-inspired AI and neuromorphic computing, to cognitive robotics. The HBP has been a driver of these developments, pushing the boundaries in both directions. The simulation platforms that have been developed offer simulation engines at the molecular, cellular, brain region and whole-brain levels. These can be connected to each other in "co-simulation" approaches to perform virtual experiments across brain regions and spatial scales, in the brains of different species. Bottom-up simulation has been combined with top-down approaches, and researchers verified their models against empirical data. Moreover, the development of human, rodent and monkey brain atlases, populated with FAIR (Findable, Accessible, Interoperable and Reusable) research data, have set new standards in the field and inform our modelling and simulation efforts. The latter have found their way into ground-breaking medical applications, where they support personalised brain models.

This report provides an overview of the scientific, data management, technological, medical and societal impact. We show how the HBP has strengthened neuroscience exploitation and conclude with a perspective on the next decade of digital brain research.

HPB Facts and Figures

500+
RESEARCHERS

155
INSTITUTIONS

19
COUNTRIES

607
MILLION EUROS
INCLUDING PARTNER CONTRIBUTIONS

10
YEARS

3,000+
PUBLICATIONS

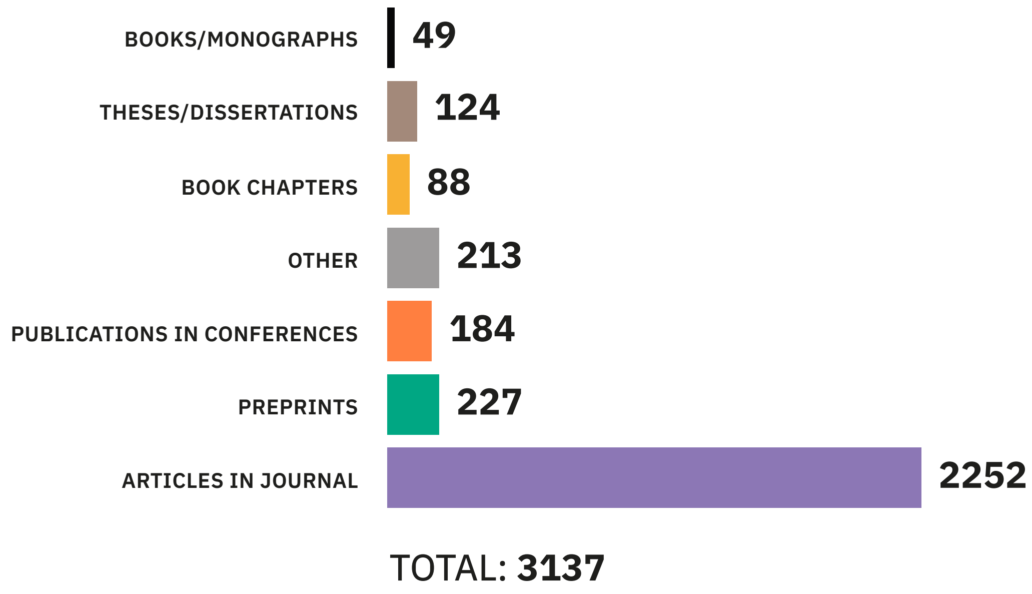
92
PATENTS FILED

12
SPIN-OFF COMPANIES

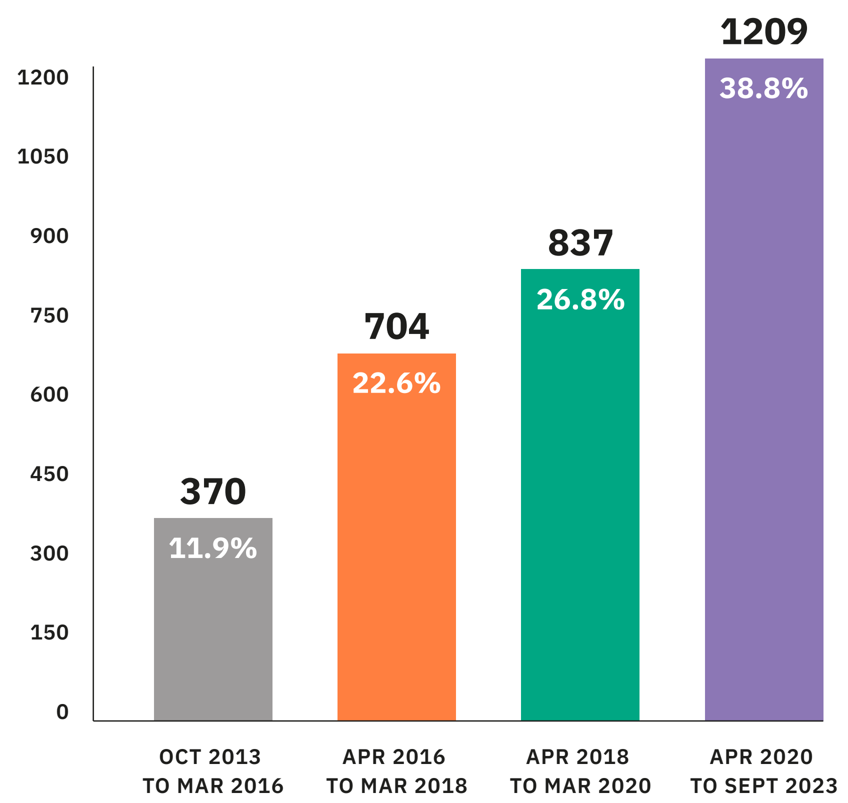
1
INFRASTRUCTURE FOR
BRAIN RESEARCH: EBRAINS

In addition to the 155 core partners, 33 further organisations from 15 countries were associated members of the HBP in the context of 76 Partnering Projects.

Number of HBP publications by type (as of September 2023)



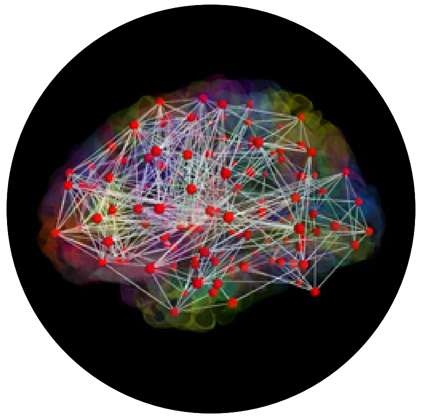
Number of HBP publications by project phase



Scientific impact

"I see a great potential for the facilities that the Human Brain Project — and in particular its EBRAINS infrastructure — has to offer. We developed a modelling pipeline for implementation in The Virtual Brain on EBRAINS so that the community will directly benefit from our work. This work will advance epilepsy research and also provide a grounding for developing patient-specific computational models of other brain disorders."

Karl Friston, Scientific Director at the Wellcome Trust Centre for Neuroimaging at University College London, who joined the HBP as part of the Lead Scientists programme.



The Virtual Brain enables computational models of the brain on the network scale.
© Jan Paul Triebkorn, Aix-Marseille University

A rich toolbox for understanding the multilevel organisation of the human brain

The human brain is organised across many scales and has been described in a multitude of different aspects by different specialised scientific approaches and disciplines. But all of these descriptions in the end reflect one system, where all of the different elements interact with each other. The major challenge to advance our understanding is thus to better integrate our insights into a coherent whole. HBP research on the human brain provided new concepts, knowledge, datasets and tools for a better understanding of the brain's multi-level and multi-scale organisation. The rich toolbox and strategies developed for this multi-scale era of brain research are available on EBRAINS in the form of high-resolution multi-scale atlases, computational models, reproducible workflows and advanced digital tools that can be applied across multiple scales.

Key data and insights on the rodent brain

Studies with rodents have been fundamental for advancing our understanding of the brain. Mice models serve as a valuable model for human diseases and allow the study of genetic, molecular and cell biological processes, as well as cognitive processes, in living animals. Through an unprecedented interdisciplinary effort, HBP researchers generated structural and functional data that enable modelling and simulating the mouse brain, focusing on four major brain regions: the neocortex, hippocampus, basal ganglia and cerebellum. In collaborations with different international teams, HBP scientists generated concepts, knowledge, experimental datasets and tools to construct standalone and multi-scale models of the rodent brain. This wealth of datasets covers molecules, synapses, single cells, brain regions, genetic and physiological data, and more. This knowledge was leveraged to improve our understanding of the human brain, filling gaps impossible to address solely in human subjects.

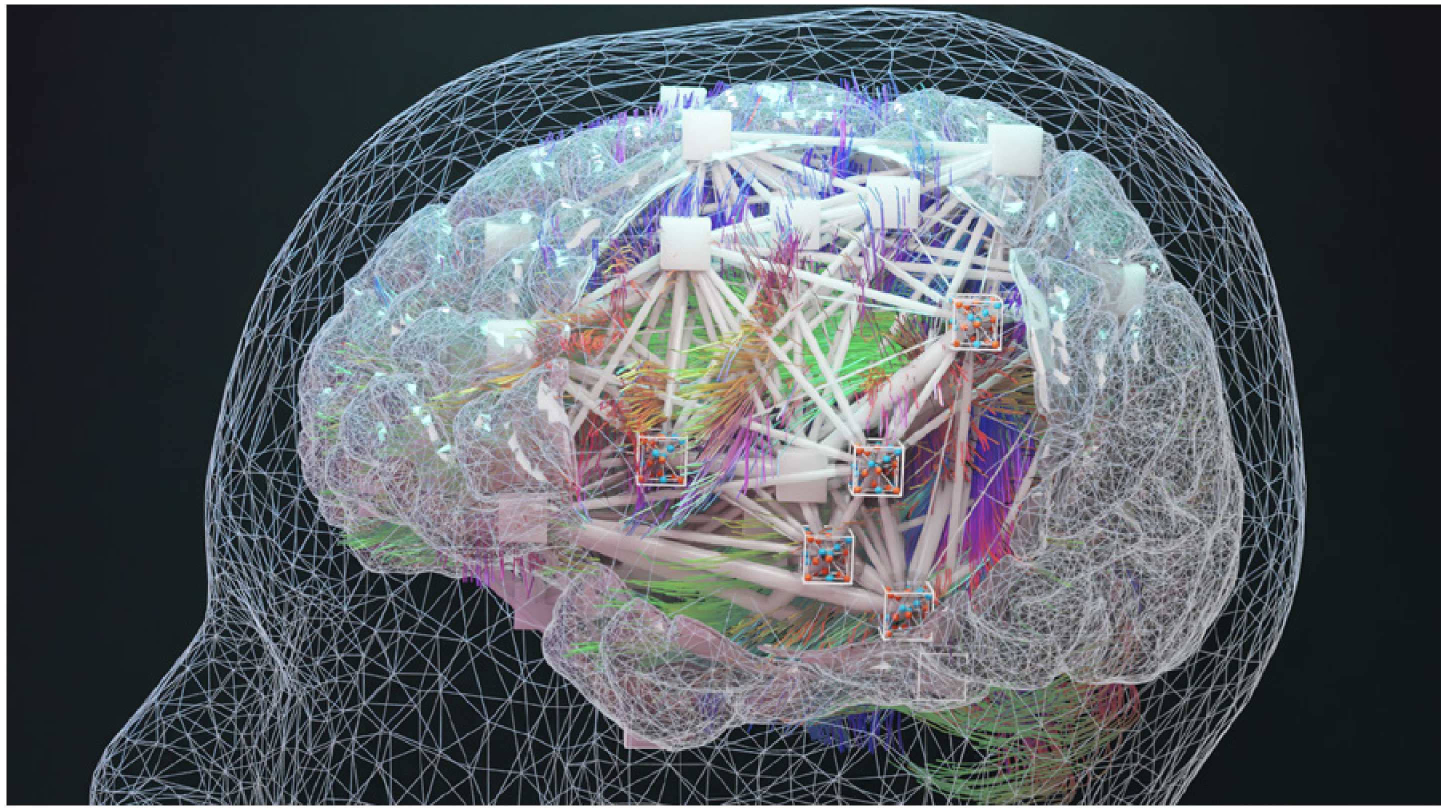
Brain models and simulation brought impact for basic science, medicine and AI

Multiscale brain modelling was at the core of the HBP, as it allows the molecular and cellular properties of neurons and circuits to be connected to the large-scale assemblies governing whole-brain dynamics. These scientific approaches have been translated into strong applications for brain medicine and neurotechnology. In particular, the Virtual Epileptic Patient technology is being applied in a clinical trial to improve surgical interventions to treat epilepsy, while The Virtual Brain (TVB) simulation of dementia is leading to new disease classifications, based on patients' brain pathophysiology. Co-simulations, using multiple software tools simultaneously, are allowing scientists to study specific neurons and circuits in detail, while also monitoring how they interact with the rest of the brain. Modelling has helped advance our understanding of the microcircuits of the cerebral cortex, hippocampus, cerebellum and basal ganglia brain regions. Spiking neural networks of these circuits are being implemented in hybrid neurocontrollers and are inspiring new technologies for autonomous learning and closed-loop sensorimotor integration in robotics.

Brain models for robots to explore embodied cognition

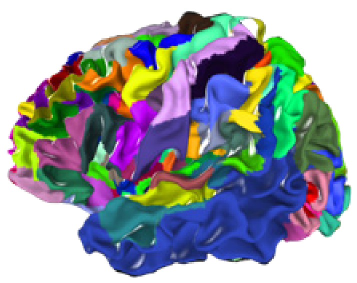
Human cognition is grounded in bodily experiences within the physical world. Scientists in the HBP combined brain modelling and robotics to reach a new path to emulate this interaction. Researchers are connecting brain-inspired deep learning to biomimetic robots to teach them more human-like capabilities. Teams from Spain and Italy have equipped robots with detailed simulation of the cerebellum and hippocampus, parts of the brain that are involved in motor control and spatial navigation. Researchers from the Netherlands and the UK have used the EBRAINS Neurorobotics Platform to teach robots how to remember places and improve autonomous navigation. Another team from the Netherlands has simulated a robotic hand developed by the Shadow Robot Company to study how the brain coordinates hand movements. The work improves our understanding of embodied cognition in the brain and opens new paths to overcome current limits in AI and robotics.

Different layers of a personalised brain network model.
© Charité/Petra Ritter



> "We leveraged the microstructural information of the HBP's Human Brain Atlas to constrain the imaging data in order to predict dopaminergic drug effects and shared our unique human dopamine dataset."

Roshan Cools, Professor of Cognitive Neuropsychiatry at the department of psychiatry of the Radboud University Nijmegen Medical Centre and principal investigator at the Donders Institute for Brain, Cognition and Behaviour (Centre for Cognitive Neuroimaging), who joined the HBP as part of the Lead Scientists Programme.



The Multilevel Human Brain Atlas contains more brain areas than ever mapped before.
© Hartmut Mohlberg, Katrin Amunts, INM-1, Forschungszentrum Jülich

World-leading brain atlases integrate multimodal data

Brain atlases are invaluable tools for basic and clinical brain research. The HBP has provided leading brain atlases for human, rat and macaque. The human atlas provides multilevel anatomical reference maps, down to the micrometre level. Maps of more than 200 individual brain areas have been made available, most of them described for the first time. It includes the BigBrain – a full 3D model at microscopic resolution. This innovative concept allowed linking the macro with the micro scale. The human atlas also features probabilistic maps of deep and superficial white matter fibre bundles, capturing variability and structure of fibre architecture at the macroscopic scale.

These maps are based on diffusion MRI and tractography as well as microscopic fibre architecture imaged with 3D Polarized Light Imaging (PLI), and functional data. The atlas was the basis for obtaining a better understanding of brain organisation, biologically realistic models and simulation, and identifying previously unknown microstructural correlates of cognitive functions. It has also been used to identify more precisely various disease mechanisms and phenotype-genotype relationships, and to support the development of new therapeutic options. The siibra tool suite allows users to automate their work with the atlas. These digital tools allow the atlas data to be integrated into simulation models.

Leading atlases were also created for animal models. The Waxholm Space (WHS) rat brain reference atlas in EBRAINS features 224 delineated brain regions, including 112 new structures and 58 revised delineations. The main new features of the atlas are detailed, expert-defined subdivisions of the cerebral cortex, basal ganglia, and thalamus. The atlas has been released with a hierarchical organisation of structures. It has been downloaded more than 30,000 times and is already utilised commercially. A new macaque atlas combines MR imaging and high-resolution brain maps of 88 areas. The borders between these areas were identified using a quantifiable cyto- and multi-receptor architectonic analysis and used for first comparative analyses across species.

Advanced data tools for neuroscientists

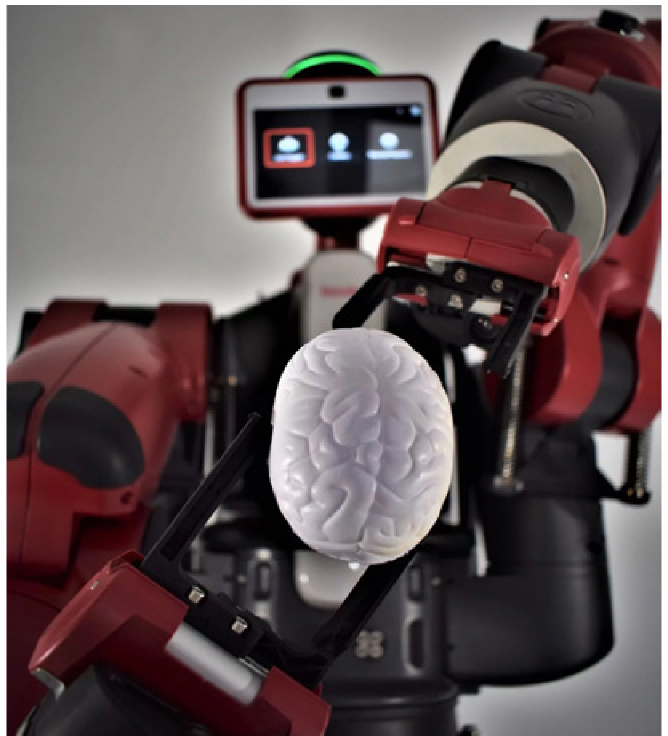
The HBP has developed advanced tools and services for neuroscientists to make their data easier to find and share. In this way, the HBP has greatly contributed to improving research productivity. The tools and services are openly available via the EBRAINS infrastructure and have already been applied by research teams from within and beyond the HBP. The technology and processes developed are also of direct use for scientific domains beyond neuroscience.

EBRAINS enables researchers to easily access and explore diverse types of data related to the brain. The platform also makes it easier for researchers to share their own data by providing expert support with data curation.

EBRAINS has been recommended as a go-to repository for neuroscience data by scientific journals including *Nature Scientific Data* and *Frontiers in Neuroinformatics*.

The HBP has developed and refined a plethora of digital tools for the analysis of brain data filling a gap in the neuroscience software landscape. Solutions developed within the project serve as a blueprint for future interactive tool integration efforts, such as EOSC-Life.

Robot controlled by an artificial cerebellum.
© Ignacio Abadía



Technological impact

The TGCC computing centre of the French Alternative Energies and Atomic Energy Commission (CEA) is part of the Fenix infrastructure.
© ICEI Consortium Partners

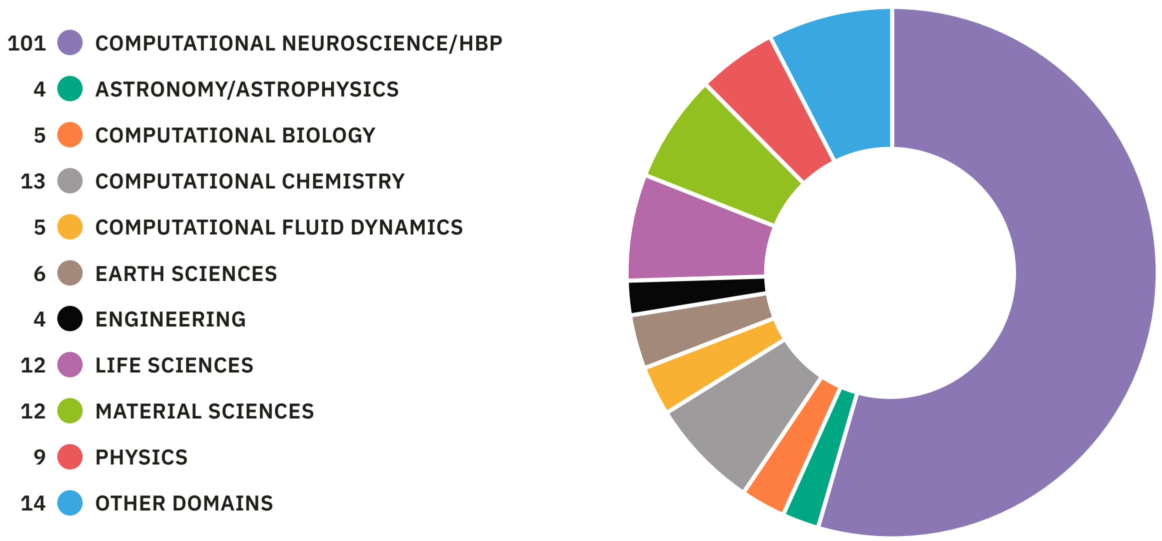
Harnessing high-performance computing and cloud capabilities to advance neuroscience

The HBP has shown that neuroscience can advance information technology but also that information technology helps to advance neuroscience. The project has made high-performance computing (HPC) and data capabilities accessible to and usable by neuroscientists, and it has equipped neuroscientists to exploit them. The resulting increase in research capabilities demonstrates that digital neuroscience has come of age.

In 2016, access to HPC resources was made easier for brain researchers within the project via two pilot HPC systems. This did not only drive the use of HPC for brain research early in the projects but also helped HPC experts to better understand the needs and requirements of the neuroscience community. It quickly became clear that the critical need was not so much access to large-scale HPC systems, but rather a data infrastructure and cloud resources closely connected with both novel interactive and classic scalable supercomputing systems. This need was met by leading European HPC centres in the HBP – BSC (Spain), CEA (France), CINECA (Italy), CSC (Finland), CSCS (Switzerland) and JSC (Germany) – joining forces in the Fenix research infrastructure to deliver the required capacities. Even though Fenix has been designed to meet the needs of brain researchers, its setup is generic enough to also allow other research communities to leverage Fenix infrastructure services for their research. The immediate impact of Fenix is reflected by increased usage of HPC resources.

At the start of the HBP, only a handful of neuroscience projects had HPC resource allocations, whereas Fenix has given allocations to over one hundred neuroscience projects, including for modelling and simulation, machine learning, imaging, and hosting of user-facing services and provision of training and workshops. This increased access to HPC is an important prerequisite for achieving the original aim of large-scale, detailed brain simulations on future exascale supercomputers. When the first two EuroHPC Exascale systems at Forschungszentrum Jülich and at GENCI/CEA become available in 2024 and 2025, respectively, the neuroscience community will have a first set of pioneering applications ready to run on these systems.

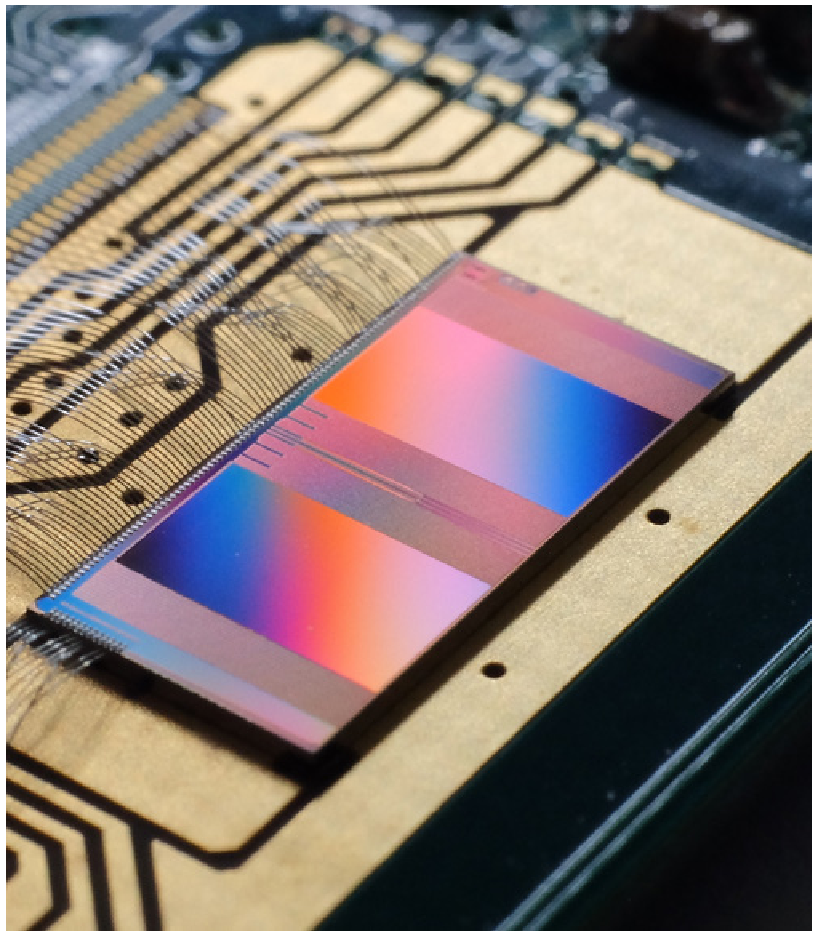
Domains of all projects using Fenix RI resources



Neuromorphic computing - learning from the brain for more efficient AI technology

Energy consumption is one of the main problems facing modern computing. The HBP has tackled the efficiency issue, potentially changing how computers will be thought of and designed in the future. The approach developed in the HBP, "neuromorphic computing", takes inspiration in various forms from the biological brain to deliver computing systems with more brain-like capabilities and energy efficiency than conventional computer architectures. The HBP has delivered the premiere European large-scale neuromorphic systems, BrainScales and SpiNNaker, both openly available to brain and AI researchers via the EBRAINS research infrastructure. It has also developed the second-generation SpiNNaker2 and BrainScaleS microchips.

BrainScaleS has supported industry research on analogue equalisation for optical communication. SpiNNaker2 is being commercialised through the Technical University Dresden spin-off company SpiNNcloud Systems GmbH, with prestigious funding grants from SPRIN-D, Germany's Federal Agency for Disruptive Innovation, and the European Innovation Council, as well as securing industry support from major companies such as BMW and Infineon, with which it is conducting pilot projects to explore the application of neuromorphic computing capabilities in their business areas.



Close-up view of a BrainScaleS-2 chip.
© Heidelberg University

Medical impact

Patient-specific brain imaging data are combined with computational models to locate the epileptic zone.
© INS UMR 1106

Neurostimulation to overcome paralysis

HBP researchers have achieved remarkable breakthroughs in neurostimulation, offering new hope for people affected by paralysis. In Switzerland, a team at the Swiss Federal Institute of Technology Lausanne (EPFL) developed personalised models for spinal cord stimulation, enabling paraplegic patients to stand and walk again. The team simulated the spinal cord of each patient in order to design and place the implants.

The result was leg and trunk motor recovery in under 24 hours. A novel device, designed for leg motor recovery by the EPFL spin-off company Onward Medical, was prototyped in a digital environment using personalised spinal cord models. The computational approaches were translated to other applications, including blood pressure regulation in a patient after spinal cord injury. The in-silico prototyping is one of the first examples of a digital twin-based therapy development for spinal cord stimulation, opening the way for European innovators to offer licensable in-silico tools to the global neurostimulation market.

Allowing the blind to see with brain implants

Work from researchers at the Royal Netherlands Academy of Arts and Sciences (KNAW) has paved the way to a future revolutionary method to restore vision in the blind. They created a device capable of transmitting visual patterns directly to the brain's visual cortex. Initial successful trials with monkeys led to testing with a small number of blind humans, which showed encouraging results. In the future system for patients, the user will wear a camera, and the images will be transmitted to the brain via electrical micro-stimulation. Based on these results, KNAW researchers founded the Phosphoenix spin-off company in 2019, which aims to create a brain prosthesis for blind users.

Leveraging data science against brain diseases

The pandemic made it clear: Health data must be better shared between hospitals in the EU and made accessible for research. The EBRAINS Medical Informatics Platform (MIP) is a HBP-developed solution to the data protection problem – locally installed software allows pooling of pre-analysed data which can no longer be assigned to individual patients, but provides valuable information to researchers accessing it. For diseases such as Alzheimer's and Parkinson's, this new data basis enables Big Data and AI-driven approaches. Rare brain diseases with only few cases per hospital may for the first time be analysed in a statistically valid way. Currently, the MIP boasts a network comprising 60 European centres. In the near future, the MIP is slated for integration into upcoming projects to create a European Platform for Neurodegenerative Diseases, and also broaden its scope to encompass domains beyond neuroscience, thereby, enhancing the utilisation and value of health data on a broader scale. In March 2023, Philippe Ryvlin from Lausanne University Hospital (CHUV) and Yannis Ioannidis from the University of Athens and their teams were awarded a HBP Innovation Award for developing the MIP. Another platform, the EBRAINS Health Data Cloud, allows researchers to store, process and share sensitive biomedical research data in compliance with the GDPR. The platform enables collaborative biomedical research using sensitive personal medical data in compliance with EU data privacy law. The platform's functional scope is currently being demonstrated in a study with 650 personalised human brain digital twins.

An open-source platform for sharing clinical EEG data

An estimated 50 million people worldwide suffer from epilepsy, with two thirds managing it with medication. For some of the remaining patients, a surgical treatment can be offered to cure their epilepsy. This involves pinpointing the seizure-generating brain region through intra-cerebral electroencephalography (iEEG) – a complex and invasive procedure performed in a limited number of specialised centres. The collected data is both rare and invaluable for enhancing our understanding of epilepsy and the broader functions of the human brain. Sharing and working collaboratively with this data is crucial for advancing clinical and cognitive neuroscience knowledge. To address this issue, the HBP has created the Human Intracranial EEG Platform (HIP), a GDPR-compliant, cloud-based, Trusted Research Environment for sharing iEEG data among healthcare researchers.

The HIP is an open-source platform available on EBRAINS and designed for collecting, managing, analysing, and sharing iEEG data at an international level. Its primary mission is to promote the development of large-scale iEEG research projects by facilitating international collaborations in the field. The HIP also provides software tools and pipelines customised for intracerebral EEG and neuroimaging analysis, within the HIP cloud, ensuring a secure environment while remaining closely connected to the pertinent datasets. Researchers can access their data and workflows, regardless of locations.

Improving epilepsy surgery with virtual brain models

In millions of epilepsy patients, pharmacological treatment is not effective and surgical intervention is the only option. HBP scientists have developed personalised brain models to identify the areas where seizures emerge in a patient's brain. The models combine inference and machine-learning methods with recordings of the individual patient's seizures. The method termed the Virtual Epileptic Patient (VEP) has previously been corroborated in retrospective studies and is now being used in a prospective clinical trial involving 356 patients with drug-resistant epilepsy.

SATT Sud-Est has granted an exclusive worldwide licence to the start-up VB-Tech for the commercialisation of the technology, which was developed by the Institute of Systems Neurosciences of Aix-Marseille University (AMU). Several patents were recently awarded for applications of the virtual brain models. AMU has also worked closely with the major industrial group Dassault Systèmes since 2018, exchanging knowledge and software technologies in the areas of simulation, modelling, 3D digital mock-ups, prediction, visualisation and information intelligence.

Measuring consciousness for better coma care

Following severe brain injury, patients may recover consciousness but remain unresponsive and, in up to 40% of the cases, be mislabelled as in a "vegetative state". For both ethical and clinical reasons, there is an urgent need to develop methods to reliably detect consciousness in patients who are unresponsive and to provide a sensitive readout of the mechanisms that are relevant for recovery of consciousness.

To address this need, HBP researchers at the Universities of Milan and Liège have developed new measures of brain complexity using fMRI, electroencephalogram and transcranial magnetic stimulation. This approach generates the Perturbational Complexity Index (PCI), which has proven highly sensitive in detecting covert consciousness in challenging clinical conditions. In a multi-scale exploration, HBP researchers have identified a mechanism known from sleep that is a key determinant of loss and recovery of consciousness. They also found that the same mechanism is responsible for network dysfunction and cognitive impairment in stroke patients. This ground-breaking work has extended beyond Europe to a multi-centric study led by the University of Milan and involving different universities in the USA.

Aiding neurodegenerative drug discovery through molecular modelling

One of the HBP's key aims was to advance our understanding of the brain by bridging multiple scales. The HBP's molecular modelling group contributed to this goal by developing multiscale workflows connecting the molecular level to the subcellular one using molecular simulation tools. The team has applied for several patents for drug candidates against neurodegenerative disorders identified using molecular simulation. The workflows and tools were also applied to investigate the molecular mechanisms leading to Long COVID. This work aimed to develop, optimise, and expand new drug candidates against SARS-CoV-2-induced inflammatory responses by targeting the main protein effector involved in the mechanisms leading to brain disorders and neurodegeneration.

Magnetic stimulation and EEG readings are used to measure a patient's level of consciousness.
© Russ Juskalian

Social impact

The HBP has brought together interdisciplinary research teams.
© mattjeacock/iStock

Training the next generation of brain scientists and building a community

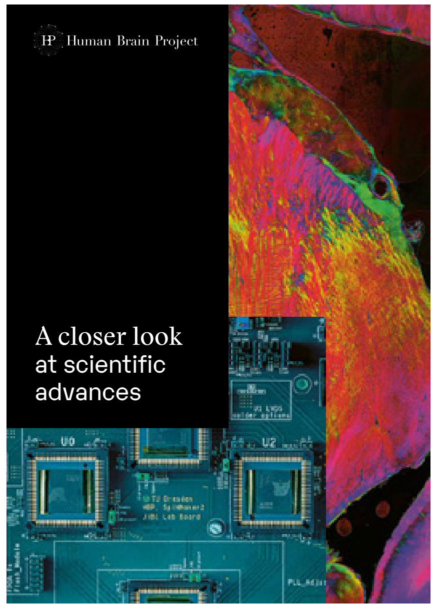
Interdisciplinary work across neuroscience, medicine and computer science was central to the HBP's "modus operandi". An Education Programme was conceived to equip a new generation of young researchers to work more effectively in this new interdisciplinary research environment, implemented a far-reaching programme of courses designed to equip researchers to expand their professional knowledge beyond the traditional bounds of their primary discipline, for example, enhancing neuroscientists' understanding of IT tools and programming providing practical training in the use and exploitation of the HBP-developed tools and services offered via the project's EBRAINS research infrastructure. Over the duration of the Education Programme, more than 1,300 lecturers volunteered to provide teaching and training for events across Europe and an E-library with over 700 educational videos. The HBP Education Programme has been very successful at transmitting the knowledge generated by the HBP to students and new users of the RI with 96 training and educational events that attracted more than 5,500 participants since 2013. Key to digital neuroscience taking hold was also the strong presence of the Human Brain Project and EBRAINS at high-level conferences with thousands of invited talks, self-organised conferences and workshops, booths at the leading US and European conferences SfN and FENS, and the annual Flagship event - the HBP Summit.

Shaping global neuroethics and Responsible Research and Innovation

As a complex project bringing together neuroscience, computer science and other disciplines, the HBP recognised the need to proactively engage with ethical and social issues from the outset. The Responsible Research and Innovation (RRI) programme therefore brought together philosophical reflection and public engagement discourse with external stakeholders, scientists, technologists, and administrators to better understand the societal implications and perceptions of neuroscience research and related fields.

Key impact-generating outputs include three position papers on Data Governance, Dual Use and Ethics in AI. The HBP ethicists work on RRI contributed to a broader take up of relevant practices, for example, in the OECD's Recommendation on Responsible Innovation in Neurotechnology. An important mechanism to support the impact of the HBP's RRI-related work was the International Brain Initiative (IBI) where the HBP led the working groups on neuroethics and data governance that worked on international agreement on those topics.

Based on the RRI experience gained in the HBP, the ORBIT-RRI start-up company was founded offering the RRI teaching facility EMBRACE.



For an overview of the Human Brain Project and its achievements, find these brochures online:
humanbrainproject.eu/science-development/scientific-achievements/brochures/

"I met my future employer via an HBP Education event, and I have first-hand accounts from dozens of scientific careers taking their first steps via HBP workshops and Young Researchers' Events."

Jens Egholm Pedersen, KTH Stockholm and Student Ambassador in the HBP Education Programme

Engaging the public with brain science

The HBP made an extensive impact in communicating the developments in brain science to the broader public. A dedicated Task Force for Science Communication produced high-quality content, written for scientific and non-specialist audiences. In particular, the Task Force produced several accessible brochures and booklets in both printed and digital form presenting the scientific achievements of the HBP. HBP scientists provided expertise in many media interviews explaining new developments in brain science and related fields and were sought-after speakers at public science festivals around Europe. Many events and workshops were held informing and exchanging with wider society, political stakeholders and patient organisations. The "Open Day" at the annual Human Brain Project Summits attracted many visitors in different European cities.

Accessible exhibitions about digital brain sciences were held in collaboration with partners ranging from science museums to parliaments including at the Scientific Foresight Unit (STOA) of the European Parliament, the Bloomfield Science Museum Jerusalem, Copernicus Science Center in Warsaw, the German Bundestag, the North Rhine-Westphalian Landtag Düsseldorf as well as several public locations in Marseille.

Lastly, digital and social media formats were used to great success to reach the public, providing updates to almost 40,000 followers on X, 70,000 followers on LinkedIn and over 4,000 Newsletter subscribers and the project website has regularly attracted more than 15,000 monthly visitors. Nearly 5,000 individual citizens and stakeholders have participated in discussions on ethical and societal aspects of the HBP and EBRAINS.

Overview and spotlights on HBP innovations

▲
HBP research has contributed to targeted spinal cord stimulation that has helped patients with paralysis walk again.
© EPFL/Jamani Caillet

Exploitation metrics	Value
Developed tools (including middleware)	160+
Main exploitable tools (scientific/data/medical/technological/social)	65 (13/14/13/25/2)
Patents filed	92
Patents awarded	12
Start-ups created	12
Start-ups planned	4
Industrial cooperations	40+
Commercial companies integrated in HBP Consortium	8

Innovation in numbers

HBP research has enabled a number of innovations in the realms of neurology, artificial intelligence and computing technology. Successful cooperation of HBP members with industry has brought science-based innovations closer to the market. In total, HBP partners have filed 92 applications for patents in 15 jurisdictions and were granted twelve patents in four jurisdictions. Twelve start-ups that commercialise HBP results have been founded in recent years. Examples include SpiNNcloud Systems in Germany, VBtech in France, Intrinsic Powers in Italy, Onward Medical in Switzerland and the Netherlands. This is just the beginning of the HBP's innovation impact, as more is expected to follow after the end of the project, which itself was much more application-oriented than the previous phases.

In sum, the HBP has seen exciting developments at the interface between science and application, in the form of industrial collaboration, interaction with business angels and investors, launching of spin-offs, licensing, and developing clinical trials.

Some of the innovations highlighted next are direct results of HBP activities, while others are built upon breakthroughs that have been achieved by the project:

Patents for new drug candidates

HBP researcher Giulia Rossetti from Forschungszentrum Jülich has applied for patents for drug candidates against neurodegenerative disorders identified with molecular modelling and simulations. She is now building on this work using Fenix computers and EBRAINS to further investigate these candidates. Currently, she is focussing on the molecular mechanism leading to long COVID and its effects on the brain in a collaboration of several HBP Partners called BRAVE. The team is investigating how inflammatory reactions in the brain can be averted; these reactions are implicated in the long-term “brain fog” experienced by many, even long after infection has been overcome.

Brain-inspired computer SpiNNaker2 in industrial pilots with Infineon and BMW

The brain-inspired supercomputer SpiNNcloud has been selected as one of the first breakthrough innovations by SPRIN-D, Germany’s Federal Agency for Disruptive Innovation and has won a prestigious European Innovation Council (EIC) Transition grant. It builds on research within the HBP on the SpiNNaker neuromorphic computing system. The next generation of SpiNNaker – SpiNNaker2 – has been created by teams at TU Dresden and the University of Manchester, together with chipmaker GlobalFoundries and German chip design house Racyics. Commercialisation is already underway in the form of SpiNNcloud Systems GmbH, a spin-off of TU Dresden. SpiNNcloud Systems delivers solutions in brain-inspired AI, from small-scale edge nodes to the large-scale SpiNNcloud composed of 70,000 SpiNNaker2 chips, which is the largest platform for real-time AI worldwide. Industrial pilot projects with BMW, Infineon and others already use the new system. SpiNNcloud and SpiNNaker2 will advance impactful AI models in computer vision, robotics, industry 4.0 and autonomous systems, where fast reaction times, low latency and energy efficiency are essential.

HBP researchers combine data from magnetic resonance imaging and stereoelectroencephalography of people with epilepsy with computational models to locate epileptogenic zones.
© INS UMR 1106

Spin-off company VB-Tech develops virtual brain models

SATT Sud-Est has granted an exclusive worldwide license to the start-up VB-Tech for The Virtual Brain (TVB) technology developed by the INS (Institute of Systems Neurosciences) of Aix-Marseille University. The technology targets the treatment of brain pathologies and combines neuroscience, brain modelling and machine learning, which together have enabled a first clinical trial in epilepsy. Several patents were recently awarded for TVB applications. This use of computational modelling in the clinic has been pioneered by Viktor Jirsa within the HBP. In 2021, he and his team received one of the first HBP Innovation Awards for this work.

Collaboration with Dassault Systèmes for epilepsy clinical trial

The EPINOV collaboration works to improve epilepsy surgery through personalised brain modelling. The approach is being tested in a large-scale clinical trial in France. The collaboration involves industry partner Dassault Systèmes, the largest company for 3D experience in Europe. The clinical trial is expected to conclude in 2025. If successful, Dassault could provide the brain-modelling software as a product to clinics.

Innovation to detect consciousness in coma patients

Marcello Massimini from the University of Milan, and his team, received one of the first HBP Innovation Awards 2021 for his innovative approach for detecting consciousness in coma patients. The approach uses combined transcranial stimulation (TMS) and EEG measurements of brain waves. It has been comprehensively refined, tested and advanced in the HBP, and its base mechanisms are better understood through EBRAINS modelling. Now, Massimini is preparing for larger steps: together with Finnish company Nextstim, which specialises in targeted brain stimulation, the UMIL team is testing a brand new TMS-EEG prototype device in Milan. Moreover, with support from the Tiny Blue Dot Foundation, TMS-EEG devices have been shipped to major US neurological hospitals, in preparation for a multi-centric clinical trial of the consciousness-measuring method. Finally, a spin-off was recently incorporated to facilitate the introduction of this method into hospitals.

Collaboration with Intel for a neuromorphic breakthrough

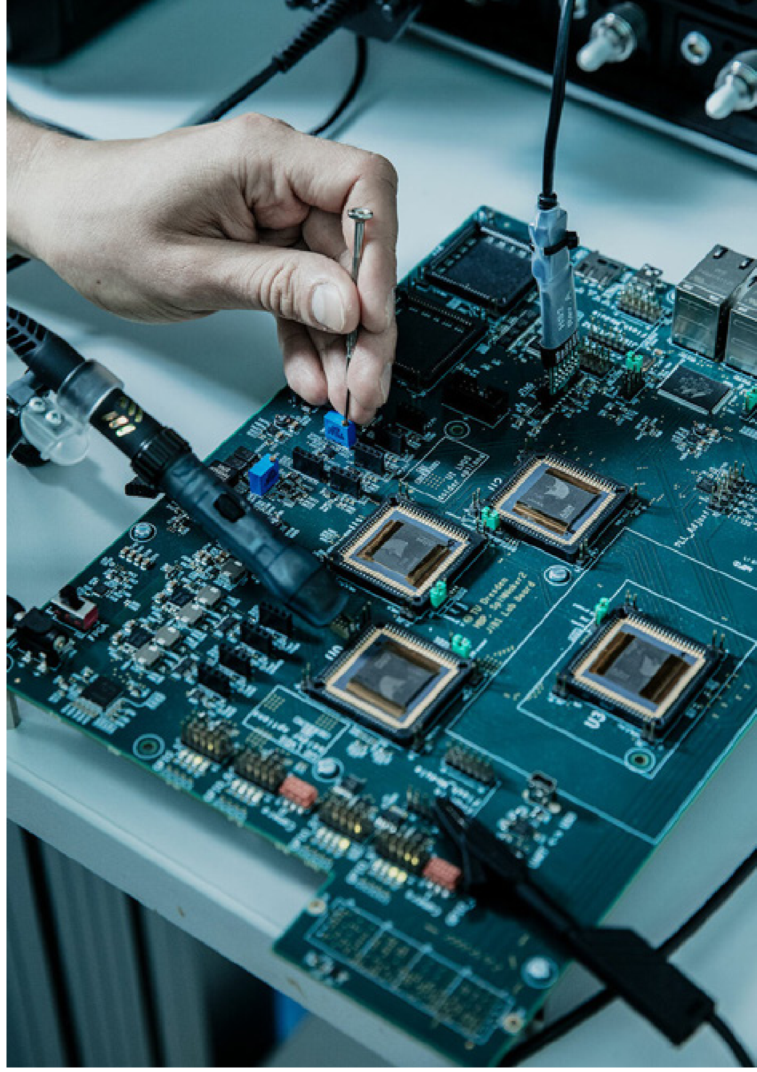
In 2022, HBP researchers at TU Graz in Austria collaborated with Intel to bring AI closer to the energy efficiency of the brain. The team develops brain-inspired algorithms which can be implemented on spiking neuromorphic systems of the EBRAINS infrastructure or external industry collaborators. The latest result, an up to 16-fold decrease in energy demand on Intel’s Loihi Chip, was published in the prestigious journal Nature Machine Intelligence. This demonstration is a major step toward new AI algorithms that function with only a fraction of the energy demand while exhibiting enhanced performance.

EPFL spin-off Onward Medical helps paraplegic people walk again

Onward Medical is a spin-off of HBP Partner EPFL that develops a treatment for people with paralysis after spinal cord injury using targeted electrical stimulation through a neuroprosthetic implant. Within the HBP, the research team behind this approach created simulation models of spinal circuitry that are used to guide the placement and design of the electrodes. This early cooperation has contributed to a series of sensational breakthroughs with this approach. Today, even patients with complete sensorimotor paralysis have been helped to regain their movement. In 2021, Onward Medical made the major step of becoming listed on the European Stock Exchange Euronext.

NIN spin-off company Phosphoenix working to cure blindness

Blindness is curable – that is the credo of the Dutch company Phosphoenix, a spin-off by HBP Partner NIN Amsterdam. The company aims to commercialise an approach that uses direct stimulation of the visual areas in the brain to evoke visual perception via an implant. Connected to a camera, this can enable some basic vision functions for blind people. As final application in humans will require very precise knowledge of the structure and dynamics of the visual field, the team collaborates with brain mapping and perception researchers in the HBP. In 2022, Phosphoenix went into a successful pre-seed funding round and licensed NIN patents for the prosthesis design. In 2023, Pieter Roelfsema and his team received a HBP Innovation Awards for this development.



SpiNNaker2 circuit board © sprind.org

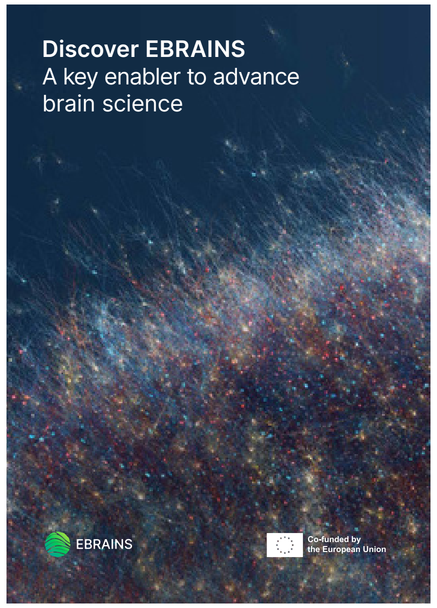
EBRAINS: A key enabler for advancing brain science

EBRAINS

The development of the EBRAINS infrastructure represents a significant milestone towards advancing our understanding of the human brain based on the foundational work of the HBP. In 2016, the HBP developed six research platforms that were opened to the community. Research and technology development paved the way for the establishment of EBRAINS in 2018. EBRAINS makes it possible to combine digital research tools into multi-scale research workflows. As these integrated efforts advance, collaboration across deeply ingrained borders of different sub-disciplines and often siloed communities is becoming ever more seamless. This is the unique benefit of an integrated infrastructure – it helps connect scales, efforts and people. EBRAINS operates as a collaborative research infrastructure in digital neuroscience, providing access to brain atlases of different species, unique datasets, multiscale models and a wide range of software tools. What sets EBRAINS apart from other infrastructures is its unique approach of seamless interoperability. This was accomplished by a co-design process between neuroscientists and computer engineers. Flexible and customisable workflows are powered by advanced HPC systems.

The integrative strategy of EBRAINS has fuelled progress in our understanding of the human brain, development of neurotechnology and personalised medicine, as evidenced in an impressive number of publications. This strategy is pivotal for the development of the next generation of virtual brain models – digital brain twins –, which will be an important part of digital brain research in the coming decade.

EBRAINS plays a crucial role in consolidating existing national infrastructures. The EBRAINS community exemplifies open science, sharing data and knowledge and working across disciplines, institutions and borders. EBRAINS will remain at the service of the neuroscience community long-term even after the HBP has ended. EBRAINS is listed on the ESFRI Roadmap for Research Infrastructures and is a member of the European Open Science Cloud (EOSC).



Learn more about EBRAINS and its services in this online brochure:
ebrains.eu/discover-ebrains

EBRAINS Facts and Figures

2,120
CONTRIBUTORS

1,029
DATASETS

224
TOOLS

250
MODELS

8,475
RETURNING USERS*

1,491
USER INSTITUTIONS

11
NATIONAL NODES

*over 12 months September 2022–September 2023

Digital neuroscience has come of age

The HBP has pioneered digital brain research.

"It is hard to imagine any other object of research that poses as much challenge and opportunity as the brain. It is what makes us human, it determines our health and wellbeing in many ways, and it inspires our technology in the information age. As we enter into a new era of brain science, equipped with powerful new tools to embrace neural complexity, groundbreaking applications of this research have begun to make their mark on European society, transforming medical practice and making the jump to market impact."

Katrin Amunts, Forschungszentrum Jülich and University and Heinrich-Heine-Universität Düsseldorf, HBP Scientific Research Director

HBP researchers have made significant contributions to our understanding of the complexity of the human brain with important implications not only for neuroscience but also for brain medicine and the development of neuro-derived technologies. In many ways, the HBP has permanently changed the way brain research is carried out. It has brought communities from different disciplines together to work collaboratively on common goals. With the open infrastructure EBRAINS, the HBP facilitates cross-border collaboration not only within Europe but also between large-scale initiatives from different continents. EBRAINS offers access to state-of-the-art tools and services that have been developed within the HBP.

When the HBP consortium proposed the HBP as an EU FET Flagship in a public report titled "The Human Brain Project: A Report to the European Commission" back in 2012, it presented four goals, which would build on existing work, while also acting as a catalyst for new research:

- To produce and share data to seed brain atlases, build models and catalyse contributions from other groups.
- To identify mathematical principles underlying the relationships between different levels of brain organisa tion and their role in the brain's ability to acquire, repre sent and store information.
- To build ICT platforms as integrated systems offering services to neuroscientists, clinical researchers and technology developers that accelerate the pace of their research.
- To translate first draft models and prototype technologies into applications, demonstrating how the platforms can be used to produce results with immediate value for basic neuroscience, medicine and computing technology.

The HBP has successfully reached these ambitious goals, providing EBRAINS as an integrative ICT-based research infrastructure and generating results that have contributed to a deeper scientific understanding of the brain, improved medical treatments and advancement of digital technology. In 2021, EBRAINS was added to the influential ESFRI Roadmap for Research Infrastructures – a strong demonstration that it is on track to becoming a fixture in the European research landscape. EBRAINS is now transitioning into a sustainable infrastructure that will remain available to the scientific community as a lasting contribution of the HBP to global scientific progress.

Over the years, the HBP has opened up more and more to the community, by putting initial concerns to rest that the project may not be inclusive enough. The open collaborative approach of the HBP has also resulted in the HBP-inspired position paper "The Coming Decade of Digital Brain Research" authored by one hundred researchers, many of which are non-HBP scientists, and endorsed by many beyond the HBP as supporters.

The paper recommends eight future avenues of research that can build on and exploit the research and infrastructure legacies of the HBP and address key societal needs:

- Multi-level brain atlas and high-resolution brain models
- Multi-level brain models and simulation
- Brain plasticity, learning and adaptation during the entire lifespan
- Neuromorphic brain models for bioinspired artificial intelligence
- Cognition and behaviour
- Brain as part of the body
- Digital brain medicine
- Bridging the gap between human and machine intelligence

"Computational neuroscience gives us interdisciplinary approaches to develop novel diagnostic tools and treatment options not just for epilepsy. There are brighter futures in sight for people currently not benefitting from the existing treatment pathway."

Simon Privett, Epilepsy patient and leader of patient expert groups

The breadth of support for this paper demonstrates the considerable community convergence on these research topics. It also shows, more broadly, that digital neuroscience has come of age and has entered the mainstream of the discipline.

This paradigm shift is far from a purely academic affair. Digital neuroscience is a crucial step towards real-life science-based benefits for society. European citizens stand to profit from more integrated knowledge of the many subfields of brain research that is now becoming actionable for medical and technological progress.

Pioneering Digital Neuroscience

How the 10-year Human Brain Project has transformed brain research.

HUMAN BRAIN PROJECT

Pioneering digital neuroscience:
How the 10-year Human Brain Project has transformed brain research.

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