Frontier Interdisciplinary Strategy

Toward the Emerging Frontiers of Brain Science and Brain-Inspired Technology

Toward the Emerging Frontiers of Brain Science and Brain-Inspired Technology Research Team

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Abstract

Brain science explores the nature of cognition, consciousness and intelligence, and is the "ultimate frontier" for human beings to understand nature; inspired by it, brain-inspired technology develops machine intelligence such as brain-inspired devices and robots. This interdisciplinary field relies on the integration of biology, medicine, information science and other disciplines to promote the innovation of neurobiology, psychology and other disciplines, and deepen the social sciences such as law and economics. Brain science drives the development of frontier branches such as bioimaging and data science, while brain-inspired technology promotes the optimization of artificial intelligence algorithms, enabling applications such as automatic driving and intelligent medical treatment. Brain science and brain-inspired technology are expected to produce significant research results in national health, intelligent industry, social development and national security, which have far-reaching social, economic and military strategic significance.

This report discusses the key scientific questions and the core technical problems in brain science and brain-inspired technology. In this field, China has actively participated in the international frontier of brain science, established a series of international facilities with advanced technologies, and made a number of international leading achievements in brain science theory, technology and application research. This project studies the advantages, leading teams and important research bases in the field of brain science and brain-inspired computing in China, investigates the development status of related research fields in China, and provides a basis for the strategic planning.

Based on the studies, we propose the development strategy for brain science and brain-inspired technology and present the policy suggestions.

Content

Chapter 1 Strategic Value

Brain science is a science that aims to study the nature and laws of brain cognition, consciousness, and intelligence. It is the "ultimate territory" for human beings to understand nature and themselves. Brain-inspired is machine intelligence inspired by brain cognitive science, including brain-inspired devices and brain-inspired robots. Brain science and brain-inspired technology are based on research and development in the field of brain science and crossed-pushed by the fields of cognition, information, nanotechnology, etc. Understanding the structure and function of the brain is one of the most challenging cutting-edge scientific questions in the 21st century.

Brain science and brain-inspired technology rely on the cross-integration development of biology, medicine, physics, engineering, chemistry, materials science, information science, computer science, psychology, and other disciplines.

Results of brain science and brain-inspired technology have promoted knowledge updates in neurobiology, basic anatomy, basic medicine, and other disciplines, and have become the cornerstone of psychology, medicine, education, computer science, etc. It can also push the in-depth development of law, economics, and philosophy. Brain-inspired technology relies on and drives in return the core technologies in computer science, including parallel computing, big data processing, and algorithm optimization.

The demand for technological innovation in brain science and brain-inspired research has driven the leap-forward development of cutting-edge interdisciplinary subdisciplines such as biomedical imaging, bioinformatics, cognitive science, intelligence science, data science, digital medicine, and brainsmatics.

Brain science and brain-inspired technology are expected to benefit human life and society in areas not only science, but also healthcare, information services, manufacturing, mobility, and sustainability. They have also wide applications in marketing, societies, and defenses.

Chapter 2 Key Scientific Questions

1. How many types of neurons and glia are involved in a brain? How to classify? Which characteristics play a decisive role?

2. Multi-modal, multi-scale, and cross-species standard brain mapping unveiling brain origin and evolution

3. Mapping of whole-brain connectome with specific functions such as learning, memory and cognition and the study of their interrelationships.

4. Development, evolution, and regulatory mechanisms of neurons and neuronal networks.

5. Regulation of central-peripheral information exchange and integration.

6. The origins of mental illness.

7. How to develop brain-inspired computing based on the thinking of brain science and computing science?

8. What inspiration can biological neural networks bring to deep learning? How to develop biologically plausible deep network learning algorithms?

9. Building brain-computer fusion intelligence.

10. Digital twin brain.

11. How to explain the black box problem between artificial intelligence models and human brain working mechanisms?

12. Ethical and Safety Considerations in Neurotechnology and Brain-Inspired Artificial Intelligence.

Chapter 3 Core Technical Problems to be Solved

1. Development of non-human primate models

2. Non-invasive observation of whole-brain neuronal activity and neurochemical molecular dynamics, and in vivo observation of synaptic activity

3. Mapping and analysis of neural networks performing specific functions in the whole brain

4. High-precision encoding, decoding, and regulation technology in cognitive processes.

5. Construction of large-scale spiking neural network (SNN) computing platform with model optimization techniques

6. Integrated technology of multimodal brain functional imaging and regulation for small animals.

7. Key technologies to analyze neural circuit mechanisms of brain diseases.

8. Key technologies for neuromodulation.

9. Technical problems of large-scale neural networks analysis for brain-inspired computational intelligence.

10. Artificial intelligence models based on cognitive behavioral paradigms of primates.

Chapter 4 Research Developments and Conditions

In the past two decades, brain science research has made rapid progress. Research at the molecular and cellular levels has completely changed human understanding of brain cognitive functions; the studies of awake animal behavior and non-invasive brain imaging have further improved the understanding of high-level brain functions and brain diseases; research on the mechanisms of brain diseases has accelerated the development of novel drugs for neurological diseases; research on brain function have also driven the development of the brain-inspired intelligence industry.

There are approximately 100 billion neurons in the human brain, and one neuron communicates with thousands or even tens of thousands of other neurons through synapses to form a neural circuit. The core scientific question in understanding the brain is how neural circuits composed of neurons complement functions at various cognitive levels, from lower-level sensations and perceptions to higher-level memory, attention, language, decision-making, thinking, consciousness, etc.

Over the past hundred years, neuroscience has made great progress in the study of molecules and cells at the microscopic level and the understanding of cognitive behavior and related brain regions at the macroscopic level. However, the studies of the mesoscopic level of the whole brain are still limited. Therefore, studying the structure and function of whole-brain connectome and neural circuits at the mesoscopic level with single-neuron resolution is a recognized focus currently and in the future.

In the past two decades, new technologies for the observation and regulation of brain structure and activity have emerged and played a huge role in promoting the study of brain function. From early electrophysiological recording to in vivo, real-time neuronal activity recording and regulation technology, neuroscience research technology has made leap-forward breakthroughs. Macroscopic brain imaging technology can obtain the morphology of brain tissue and electrical activity and metabolic information of multiple brain regions at the macro level. The new generation of optical imaging and optogenetic technology can observe the activities of large groups of neurons and circuits at the mesoscopic level and perform circuit-specific regulation. Fast, high-throughput, spatiotemporally specific whole-brain single-transcriptome sequencing technology provides the necessary foundation for neuron type identification, specific labeling and tracking of neural connections, and specific regulation of neural circuits at the micro level. The research and development of new technologies, including the processing, analysis, and modeling of massive data on neural structures and activities, as well as the theoretical framework for understanding the working principles of neural networks, remain serious challenges.

Chinese scientists have made great progress in the past two decades in brain science. World-recognized achievements include findings on neural circuits related to the processing of sensory information (especially vision, pain, and itch), discoveries in the neural circuit mechanisms of multi-sensory integration, sensory-motor conversion, instinctive behavior, emotion, attention, and decision-making, the establishment of research paradigms for non-human primate models (macaques and marmosets) of advanced cognitive behaviors (such as complex decision-making, self-awareness, and prosocial behavior), mesoscopic and single-neuron resolution whole-brain mapping of neural connections and in vivo observation of electrical activity of large groups of neurons.

In the field of brain-inspired computing and brain-computer intelligence technology, Chinese scientists have achieved internationally renowned results by integrating brain science research with supercomputing, mathematical analysis, and other fields. World-leading progress includes achievements in computer vision, speech recognition, machine translation, and natural language understanding. Several techniques have been transferred to the industry. In 2019, Chinese scientists successfully developed a new type of brain-inspired computing chip for artificial general intelligence - the Tianjic chip. In 2020, the world’s largest brain-inspired computer with 120 million artificial neurons and 100 billion synapses has developed. In 2023, the world's first fully system-integrated memristor computing-in-memory chip has been developed.

Realizing the importance of brain science, many developed countries launched brain initiatives. The United States announced the launch of The Brain Research Through

Advancing Innovative Neurotechnologies (BRAIN) Initiative in April 2013, aiming to revolutionize the understanding of the human brain by accelerating the development and application of innovative technologies. The European Commission announced the inclusion of Human Brain Project in the Future and Emerging Technologies (FET) Flagships in October 2013, in an attempt to gather various forces to lay the foundation for a new brain research model based on information. In 2014, Japan launched the Brain Mapping by Integrated Neurotechnologies for Disease Studies (Brain/MINDS), which employs a unique non-human primate model and aims to ultimately understand the complex human brain by mapping the structure and function of its neural circuits.

In 2021, the Chinese government has approved the funding of Science and Technology Innovation 2030 – Brain Science and Brain-Inspired Intelligence Research major project (also known as "China Brain Project"), aiming to develop a deeper understanding of the mechanisms and principles of the brain at multiple levels and promotes deep and close collaboration between neuroscientists and artificial intelligence (AI) researchers. Based on research on the neural principles of brain cognition, the China Brain Project is structured as 'one body and two wings', to develop treatments for major brain disorders and promote the development of a new generation of artificial intelligence. As part of the China Brain project, basic cognitive research on neural circuit mechanisms provides input and receives feedback from brain disorders/intervention and brain-inspired technology (two wings).

China has accelerated the investment and establishment of laboratories and institutes for brain science and brain-inspired technology in the past five years. More than 15 institutes and laboratories are approved as state or national laboratories by the Ministry of Science and Technology or the National Development and Reform Commission. Many cities invested in establishing research centers for brain science and brain-inspired technology, such as Beijing, Shanghai, Shenzhen, Guangzhou, Suzhou, Chongqing, Chengdu, etc.

Foreign and private investments have been input into Chinese brain research. The Patrick J McGovern Foundation has supported four IDG/McGovern Institutes for Brain

Research in China, cooperating with Peking University, Beijing Normal University, Tsinghua University, and Shenzhen Institute of Advanced Technology of the Chinese Academy of Sciences, respectively.

In 2020, Tianqiao and Chrissy Chen Institute (TCCI) donated 500 million yuan to its first Frontier Lab for Brain Research, operated at Shanghai Huashan Hospital Hongqiao Campus, supporting brain science research in China. In the next year, TCCI donated 50 million yuan and signed a contract with Shanghai Mental Health Center (SMHC) to jointly establish a new Chen Frontier lab focused on improving evaluation and interventions for mental diseases of large populations using big data and AI-powered analysis of individual behaviors and symptoms.

Kunming started to construct National Research Facility for Phenotypic and Genetic Analysis of Model Animals in 2019. Suzhou started to establish HUST-Suzhou Institute for Bransmatics in 2016, which owns 50 whole-brain imaging machines. Shenzhen invested 8800 million to establish Shenzhen Brain Science Infrastructure in 2020. Sanya invested 7200 million to build the Research Center for Non-human Primate Germplasm Resources and Models.

Compared to developed countries, the group of Chinese scientists in brain science and brain-inspired technology is relatively small and dispersed. Original innovative research is countable. Chinese scientists lack of experience in designing and organizing big projects and have limited international impact.

“China Brain Project” was initiated about 10 years later than other developed countries, and the actual funding and awards are less than the plan. However, fundings from National Natural Science Foundation of China and local governments are sustainable. Central and local investments in the construction of facilities and infrastructures are increasing.

Another advantage is the relatively lower cost of the materials, experiments, and labor, which may be attractive to international corporators.

Chapter 5 Development Strategy

1. Give high priority to the development of tools and methods for brain science and brain-inspired technology research.

2. Establish special funds from the national level to support independent innovation technologies, and promote the applications in China and the world.

3. Strengthen top-level design and insist on supporting bases and teams with distinctive strengths and research priorities.

4. Provide long-term and sustained funding to support research and infrastructure.

5. Cultivate the next generation of scientists and researchers.

6. Host and organize international academic conferences. Manage high-level international journals.

7. Participate in the management of international academic organizations and consortiums. Propose and initiate international big science projects.

Chapter 6 Policy Suggestions

1. Strengthen talent cultivation and train more scientists and engineers to devote themselves to brain science and brain-inspired technology fields.

2. Strengthen top-level design and layout rational research system.

3. Strengthen support to China's leading technology with independent innovation.