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China AI-Brain Research

BRAIN-INSPIRED AI, CONNECTOMICS, BRAIN-COMPUTER INTERFACES

類腦智能

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CENTER *for* SECURITY *and* EMERGING TECHNOLOGY

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Cover illustration: "Brain-inspired AI" in Chinese.

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Executive Summary

Since 2016, China has engaged in a nationwide effort to "merge" artificial and human intelligence as a major part of its next-generation AI development program. The effort is not unique to China, although China enjoys natural advantages that may expedite its success.

The term "merge" is meant both figuratively, in the sense of creating a more human-friendly AI, for example, to support human decision making, and literally, in the sense of erasing distinctions between how AI and the brain operate, and how the two forms of intelligence interact.

China's initiative involves research in three disciplinary areas: "brain-inspired" AI that models aspects of human cognition, "connectomics" or brain mapping, and brain-computer interfaces that link the two platforms. "Neuromorphic" digital-analog hybrid chips also play a role.

A review of China's statutory proclamations, enabling infrastructure, main practitioners, and scientific literature indicates the initiative is genuine and that China is pursuing the benchmark challenges characteristic of AI-brain research worldwide.

China's advantages in this area are national commitment, the world's largest supply of laboratory grade non-human primates, a more permissive experimental ethos, fewer privacy concerns on data collection and use, and an unrivaled ability to absorb and apply foreign technical advances.

Some Chinese scientists involved in this initiative believe artificial general intelligence (AGI) may someday issue from this research, but we find no indication in the materials examined that any such "breakthrough" is imminent.

Chinese scientists agree almost unanimously that international structures and agreements are needed to ensure the safety of next-generation AI, whatever forms it may take. Identifying those scientists able to lead such initiatives in China should be a U.S. priority.

U.S. ability to monitor China's AI and other high-tech development is hampered by the lack of a national STI (scientific and technical intelligence) organization. Current efforts are fragmentary, uncoordinated, ephemeral, and give the false assurance that a non-existent capability exists.

We recommend creating within the U.S. government—possibly outside its intelligence community—a centralized body of open source specialists to monitor China's AI development and foreign acquisitions, and other potentially risky technologies, on the theme of "trust, but verify."

Introduction

This paper examines China's program to combine artificial intelligence (AI) with neuroscience (NS) research, leverage synergies to address hard problems in both areas, and efforts to merge human and artificial intelligence.

In particular, we aim to:

- explain the goals of China's AI-brain program;
- identify key players, institutes, and pillars of support;
- evaluate research done in each of the major topic areas;
- determine the program's foreign dependencies; and
- take stock of its trajectory and potential concerns.

The paper begins by describing the technologies that shape China's AI-brain program (1) and benchmarks used to evaluate progress (2) as a basis for understanding points made in the study.

We then explore China's program itself: its goals and motivation (3), the statutory provisions that enable it (4), its physical infrastructure (5), and the caliber of those running it (6). A survey of its architects and practitioners is also provided (7). Finally, we evaluate the program using primary sources and expert consultation (8) as a foundation for assessing its dependencies (9). Recommendations to address potential areas of concern are given by way of conclusion.

The authors of this study thank Dr. Jennifer Wang, and CSET's Dr. Catherine Aiken and Daniel Chou for their subject matter support, help fielding the scientists survey, and data crunching expertise, respectively. We also thank the Allen Institute's Dr. Christof Koch and SOS International's Dr. James Mulvenon, who served as readers, and IARPA's Dr. David Markowitz, for many helpful suggestions. We also acknowledge with gratitude the support of our CSET directors, fellows, and research assistants.

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1 BI-AI, connectomics, and BCI

Brain-inspired artificial intelligence (BI-AI, 类脑智能) can be understood on three levels:

Most basically, all artificial intelligence is brain-inspired since "intelligence" derives from the activity of biological brains. Accordingly, human efforts to emulate intelligence on artificial platforms are brain-inspired by default. Many AI concepts, including neural nets (NN), hidden layers, and connection weights, draw inspiration from—and are analogs of—these naturally occurring "wet" phenomena.

A second level of BI-AI seeks to replicate higher cognitive skills such as intuitive reasoning, causation modeling, and associative recall, or even "simpler" skills like visually distinguishing objects from background. The "inspiration," however, owes less to detailed modeling of brain processes and more to equating machine learning successes with analogous macro-level brain behavior—whether the algorithms have anything in common is irrelevant.[1] In this sense, inspiration is a metaphor, which we characterize here as "weak" BI-AI.

A third level attempts to write accurate mathematical descriptions of brain processes that contribute to behavior, and run these algorithms on computers to reproduce the behavior. Functional equivalence is eschewed in favor of neural models that correspond directly to the "computation performed by biological wetware."[2] This line of research we characterize as "strong" BI-AI—and is the primary object of our concern in this paper.*

*Not to be confused with "strong" or "general" AI, i.e., human-equivalent artificial intelligence, although some researchers believe development of the one (BI-AI) is a precondition for the other (AGI).

Connectomics (人脑连接组) or "brain mapping" refers to empirical and computational efforts to replicate on multiple levels the structure, function, and system features of neurobiological circuitry—the mammalian central nervous system (CNS) especially.[3] While conceptually distinct from BI-AI, the two fields share the same goal of reproducing brain functionality. Connectomics relies heavily on AI because:

- Models of brain function are tested as mathematical simulations that invoke AI.
- The complexity of the brain is such that AI algorithms are needed to complete the mapping, e.g., to interpret images or to extrapolate from observable sequences.[4]

The interdependence of AI and brain study, exemplified here, creates a paradox: if a brain too complicated to understand itself builds an artifact that can (namely, AI), can a principled distinction between the two be maintained? Perspectives like this drive speculation that the two forms of "intelligence" may bootstrap one another, augmenting human intelligence,[5] and leading to their effective "merger" (混合).[6]

Brain-computer interfaces (脑机接口) further blur the distinction between "real" and artificial intelligence, potentially to the point of identity. BCIs are devices that acquire electrical signals from the brain, analyze them on computers and, optionally, translate the signals into actionable commands. BCI devices are distinguished along two dimensions: (1) read only or read-write, and (2) whether they receive input "invasively" by direct contact with in vivo neurons (i.e., penetrate the skull) or "non-invasively" through electrodes placed on or just under the scalp. Early devices could move cursors after calibration and training, but lacked precision and throughput for rapid control of complex movements and communication.

To remedy these problems, AI is now being applied in "primary BCI"* projects to digitize neuronal signals, interpret their coding schema, learn optimal features and, ultimately, diagnose and alleviate medical conditions.[7] Beyond these therapeutic uses, BCI is seen as a potential direct link to AI resources, eradicating the middleware (keyboards and mice) and opening the door to cognitive enhancement ("non-primary BCI") and related ethical issues.[8]

Collectively, these fields—BI-AI, connectomics, and BCI—constitute the three main areas of AI-brain research identified by Chinese scientists (Section 7 below) and international experts.

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*The restoration of motor and sensory function to damaged brain tissue.

2 AI-brain benchmarks and challenges

Many goals of AI-brain research are identical to those of mainstream AI, the difference being that while the latter may draw inspiration from human behavior, the former emulates particular neuronal functioning that gives rise to behavior. We summarize these matters here as a baseline for evaluating the scope of AI-brain research in China.

BRAIN-INSPIRED AI

Strong BI-AI—computationally modeling features and functions of a biological brain—aims to overcome shortcomings of "traditional" AI, such as its narrowness (proficiency at one task only), slowness (training requires repeated runs with many examples), and cost (hardware and power consumption). The human brain, weighing just three pounds, assembled genetically, and running on 25 watts, effortlessly performs many high order tasks beyond the reach of the artificial neural nets (ANNs) used in most types of machine learning (ML), and hence becomes AI's model.

Specifically, the goal of BI-AI is to "understand the computational principles of the cortex, and implement intelligent systems that operate on those principles."[9] Algorithms inferred from the actual behavior of interacting neurons are tweaked on ANNs to emulate their functionality. As described by Baylor College of Medicine's Andreas Tolias:

> "Our ultimate goal is to apply the principles and canonical algorithms we learn from cortical circuits to build the next generation artificial neural networks that will be based on a set of new computational primitives inspired by neuroscience."[10]

Put succinctly, the aim is “a less artificial intelligence.”[11] One must look beyond the nodes and edges of network architecture to other features that contribute to network function. This begins by appreciating that the “integrate-and-fire” neuron model that informs most ML is inadequate:

> “Most state-of-the-art algorithms assume static data or at best linear models in the form of primitive linear dynamical systems of hidden Markov models. The reality of neural processing is that these systems are highly dissipative nonlinear dynamic systems.”[12]

Emulating neurons and their interconnections in isolation ignores much of what happens in biological brains. Other parameters must be accounted for, such as firing (“spiking”) rates, local field potentials,* co-firing with other neurons, system wide oscillations, and chemicals outside the synaptic cleft that affect system-wide performance—not to mention connectivity with other areas of the cortex and subcortical structures (thalamus, hippocampus) needed for sensory integration and higher order functions. The contrast between real brain functioning and standard ANNs is striking:

> "(F)or a particular neuron in the brain, only 5% to 10% of the input is actually coming from the previous layers. On the other hand, a[n artificial] neural network is almost 100% learning from a previous layer. And further, in a real neuron, 90-95% of the activity is listening to neighbor or boss neurons from downstream."[13]

Replicating each of these parameters, while theoretically possible, in practice will be addressed piecemeal—and, in our view, slowly. Meanwhile, two areas of research likely to be part of an overall solution are so-called “spiking neural networks” (SNNs) and neuromorphic chips. The former is software that accommodates spatial *and* temporal excitation patterns. Neuromorphic computing is hardware that emulates biological architectures via analog or a mixture of analog and digital circuits.

*Extracellular signals caused by imbalances of ion concentrations around (outside) the cells.

SOME (ASPIRATIONAL) FEATURES OF BI-AI THAT DISTINGUISH IT FROM AI IMPLEMENTED ON STANDARD NEURAL NETWORKS[14]

- Structure and function follow those of a brain.
- Data and information are encoded and processed as **spikes over time**.
- The system can scale to trillions of connections and is highly parallel in operation.
- It allows (in theory) for "one pass" learning based on little prior knowledge.
- It is computationally inexpensive.

Other key areas of AI research of particular relevance to the BI-AI effort are:

- **Sparse coding,** namely, the ability to represent things by strongly activating a small subset of the available neurons, achieved by modeling a network's hidden states.
- **Metalearning,** or learning how to learn—in this context, teaching a system to make sense of a task, rather than learning a brittle representation of the data.
- **Transfer learning,** whereby knowledge gained in one domain is transferred to new domains, reducing learning time and potentially enabling planning and creativity.[15]
- **Context-dependent learning** meant to eliminate catastrophic forgetting, an endemic problem in ANNs, where new information erases previously learned patterns.

CONNECTOMICS*

"Connectomics" or brain-mapping is a physical process that relies on the observation of actual brain tissues for its data. It is hard for a discipline to be any less artificial. We include it in this study of AI and the brain because (1) it complements BI-AI, on which the latter depends for ground truth, and (2) AI plays key roles in the success of the connectomics project.

*We are indebted to Dr. Christof Koch of the Allen Institute for his comments on this and the following sections particularly, from which we have borrowed freely.

Connectomics aims at discovering the brain's structural linkages, functional correlations, and effective (causal) interactions.[16] The term mimics "genomics" by design, which belies its goal of creating a comprehensive map of the human brain.[17] The enterprise is based on a commonsense belief that the brain's physical wiring affects (but does not determine) the computations it can perform. Functional and effective connections are also pursued because structural connectivity is insufficient to predict behavior; it only puts a constraint on the network's dynamics.

Owing to its size and complexity, there is no full connectome of the human brain nor will one appear soon. The mapping of the nematode roundworm, with a nervous system of exactly 302 neurons, until recently was the only animal whose connectome had been completed.[18] The feat was surpassed in 2020 with completion of a fly brain connectome of some 25,000 neurons.[19] The human brain, by contrast, contains some 86 billion neurons (16 billion in the cerebral cortex), up to 50,000 synapses (chemical and electrical links between neurons) per neuron, and more than 1,000 neuronal cell types with a spectrum of different features.[20]

The connectomics literature identifies three mapping scales, each with its own challenges and methods. Macro-scale seeks to describe the structural and functional connections between all cortical and subcortical areas at the mm scale, almost always using functional imaging tools (fMRI and diffusion tensor imaging, DTI). Micro-scale connectomics maps individual neurons, glial cells,[21] synapses, and subcellular components—elements visible at micrometer* resolution using electron-microscopy. "Meso-scale" (100s of micrometers) is an intermediate level that can be acquired and exploited with current tools. Its targets are distinct genetically defined neural populations throughout the entire brain of experimental animals (mice and, soon, non-human primates).[22]

Data collection tools are of two types: non-invasive (outside the skull) imaging of in vivo tissue (e.g., magnetic resonance imaging, electroencephalography), and section preparation of deceased brain tissue into 20-40-micron slices, which are stained (embedded with heavy metals), imaged with electron microscopy, and aligned computationally to capture the original 3D configuration. AI supports these reconstructions, which are skewed by inaccuracies in the alignment tools.† By far, the biggest and most essential contribution of AI to connectomics is segmentation and labeling of the hundreds of millions of images needed for reconstruction of cortex tissue.[23]

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*Millionth of a meter, also called "micron."

† "EM approaches are used for densely mapping local connectivity. There are molecular and optical approaches available for mapping long-range interactions." Our thanks to Dr. David Markowitz for pointing this out.

Connectomics will benefit from improvements in the resolution, speed, and accuracy of imaging, (semi-) automatic machine labeling and segmentation tools, and in the sophistication of AI algorithms and graph theory. Drawing inspiration from the human genome project, there is cautious optimism within the profession that a full (microscale) connectome of a human brain can be assembled eventually.[24]

BCI

Brain-computer interfaces (BCI) are mechanisms that typically link the central nervous system with a computational device. Information is exchanged between the two—ideally in both directions, without invoking the sensory receptors—through electrodes planted on or under the scalp, inside the skull but outside the brain, or in direct contact with living brain tissue. The choice is a trade-off: performance improves with proximity to the brain, but invasiveness—besides the obvious risks of infection and bleeding—can scar healthy tissue and lead to rejection.

Historically, neuroprosthetics—devices that supplant or supplement the input/output of the nervous system—has been the main purpose of BCI.[25] More recently, opportunities for cognitive enhancement have captured the attention of commercial[26] and military[27] investors and the imaginations of others, who foresee the technical equivalent of telepathic communication, simulated life experiences, unlimited knowledge—in short, a merger with AI and the best chance for humans to avoid obsolescence.[28]

Meanwhile, serious obstacles impede this vision. One is bandwidth limitations. Non-invasive BCI records electrical activity on the scalp,* the output of which is slow and highly ambiguous.[29] Invasive devices, which give better signals, entail risk and inconvenience. Even so, the main problem is that "we simply do not understand what is going on at the relevant causal level" nor is science able to precisely identify and target the relevant neurons from which to record.[30]

The challenge, beyond these fundamental ones, is to create a sensor modality that is both safe and robust, ideally a wearable device "that can record from very large numbers of neurons simultaneously in order to create a seamless, high-throughput data link between the human brain and computers" with both "read" *and* "write" functionality.[31]

*Called "electroencephalography" (EEG). Electromyography (EMG), which records electrical activity at muscles, is being used experimentally to decode signals from the brain's speech centers.

Regardless of modality, AI's role in BCI is essential, for example, in helping resolve three contradictory performance vectors: accuracy, response latency, and multi-functionality.[32] Signals are "noisy, non-stationary, complex, and of high dimensionality," necessitating AI-dependent preprocessing and feature extraction.[33] A common language (exchange protocol) is needed for robust interaction and that medium will likely emerge in the hidden layers of an AI program.

SOME GOALS OF AI-BRAIN RESEARCH

Object/scene vision A nearly intractable problem in computer science, in part caused by the lack of data to build algorithms of the brain's intermediate vision processes.

Attention modeling Biological attention mechanisms work to prioritize and isolate information relevant at a given moment.

Continual learning Another name for the "catastrophic forgetting" problem, i.e., learning new tasks without forgetting old ones.

Episodic memory Recording of and access to personal (autobiographical) events that can be explicitly stated along with their associated context.

Intuitive understanding Including core concepts abstracted by the brain from experience or, by some accounts, present from birth.

Imagination Recombining elements familiar in one context into a new context on the basis of analogy (see "transfer learning" above).

Planning Closely related to imagination: the ability to run simulated outcomes based on internalized models.

Sensemaking Identifying relationships that situate new or ambiguous data in a familiar context.

Effective BCI Linking intact brains directly with computing resources to cure/manage illness, enhance human performance, and augment cognition.

3 Chinese scientists' goals and understanding

A review of Chinese and English technical papers, government proclamations, statements by leading scientists, facility websites, interactions with foreign organizations, and a survey of the country's principal practitioners indicate that China—officially, institutionally, and as a matter of practice—has embraced the need to "merge" (混合) AI research and brain science.

Indeed, it is probable China was exploring the intersection of human and artificial intelligence before it acknowledged the value of AI as a standalone discipline. As this and the following sections will demonstrate, Chinese scientists are involved domestically and internationally in each of the identifying features of this hybrid area, research the same sets of questions, share the tripartite BI-AI / connectomics / BCI characterization of the enterprise, and are not reticent about stating their longer-term goals of creating a "more general AI."

Although antecedents of the problem were being researched in China in 2005* or earlier,[34] the business came fully into its own a decade later with the founding of dedicated BI-AI research centers starting in 2014,† the enactment of enabling statutory provisions beginning in 2015 (see Section 4 below), and the issuance of key documents in authoritative journals in 2016 by the project's prime movers that outline China's course clearly and consistently.

We examine 12 such documents by leading Chinese scientists in each of the three research areas, including six from a core group of 2016 papers, to introduce the dynamics of China's approach.

* The earliest date for which we have consolidated Chinese language data.
† Tsinghua University's Center for Brain-inspired Computing Research (清华大学类脑计算研究中心), founded in September 2014.

1. “Retrospect and Outlook of Brain-inspired Intelligence Research” (类脑智能研究的回顾与展望). Zeng Yi (曾毅), Liu Chenglin (刘成林), Tan Tieniu (谭铁牛) in *Chinese Journal of Computers* (计算机学报), 39(1), January 2016, 212-222.

The paper reviews BI-AI developments worldwide, concludes it is the future of AI, and defines China’s near-term goals as: (1) semantic recognition of perceptual information that is both feature- and model-driven; (2) collaborative and continuous autonomous learning; (3) efficient big data computing; and (4) brain-like language processing, including semantic interpretation, knowledge representation, reasoning, and sentiment analysis. Autonomous decision-making and control will also be explored. The authors, whose affiliations span both the northern (Beijing) and southern (Shanghai) focal areas of BI-AI research in China, describe the mission as follows:

> “Its goal is to realize various human cognitive functions as well as their coordination mechanisms by machine through brain-inspired principles, and eventually reach and go beyond human-level intelligence (最终达到或超越人类智能水平).”

2. “Brain Science and Brain-inspired Intelligence Technology-an Overview” (脑科学与类脑研究概述). Pu Muming (蒲慕明), Xu Bo (徐波), Tan Tieniu (谭铁牛) in *Bulletin of Chinese Academy of Sciences*, 31(7), July 2016, *725-736*.

The authors acknowledge a worldwide “emergent trend” to fuse brain and computer sciences based on the perception that the brain’s structural organization and functional connectivity provide models to solve intransigent problems in traditional AI. AI at present is “not well adapted to real needs,” selective perception is a problem, and language understanding and pattern recognition lag. Current AI “lacks generalizability” (缺乏通用性): learned capabilities cannot be easily extended to other tasks. While deep learning has achieved successes, they are shallow and processes are expensive to run.

The brain has none of these issues. Hence, a new AI, inspired by brain research, is needed with “multi-brain area, multi-modality, and multi-task coordination as the core.” The brain’s structure, learning methods, and *mathematical foundations* (our emphasis) must be studied and applied to “realize intelligent systems with autonomous learning capabilities.”

China has advantages and disadvantages. On the plus side, a decade of state-sponsored research in brain science has positioned China to move into this area on a comparable footing with other countries (已取得了一批国际水平的成果). China’s 2012 launch (below) of a connectome pilot preceded analogous projects in the United States, Europe, and Japan. On the negative side, there is a considerable gap between China’s technical ability and that of advanced countries, especially in basic research (see Section 9) and a lack of overall planning that must be addressed.

3. “Progress and Prospect on the Strategic Priority Research Program of ‘Mapping Brain Functional Connections and Intelligence Technology’.” (“脑功能联结图谱与类脑智能研究” 先导专项研究进展和展望). Zhang Xu (张旭), Liu Li (刘力), Guo Aike (郭爱克) in *Bulletin of Chinese Academy of Sciences*, 31(7), July 2016, 737-746.

The paper surveys international developments in connectomics (brain mapping) research in part as justification for China’s own project, in part to baseline China’s indigenous goals. Zhang Xu and colleagues describe the Chinese Academy of Science’s 2012 "Brain Function Atlas Project" (i.e., functional connectomics) situated within CAS’s Institute of Neuroscience (中国科学院神经科学研究所) in Shanghai (Section 5 below), budgeted at 600 million RMB (USD 84 million) over 10 years. The project was expanded in 2015 and renamed “Brain Function Atlas and Brain-inspired Artificial Intelligence Research” (脑功能联结图谱与类脑人工智能研究), which the authors claim is “the first practical integration of neuroscience and intelligence technology fields in the world,” indicative of China’s shifting research focus to the AI-brain nexus.*

The project’s goal “is not to describe all the connections and electrical activities of all nerve cells,”[35] but to “describe the *functional connection and operation* between special types of nerve cell groups in various brain regions” (our emphasis). In particular, the project aims to “achieve theoretical breakthroughs in the study of brain functional connection maps, and clarify the organizational structure of brain functional connections [used in] perception, learning and memory, emotions, and decision-making.” Another area of research is the “neural basis of self-awareness” (自我意识的神经基础). The project aims to elevate China’s research of the brain’s cognitive basis “to the international advanced level” or higher.†

4. “The Human Brainnetome Atlas: A New Brain Atlas Based on Connectional Architecture.” Fan Lingzhong (樊令仲) and 13 others, primarily with Chinese institutional affiliations, in *Cerebral Cortex*, 26 (8), August 2016.

The paper describes China’s whole brain atlas—the cornerstone of its “Brainnetome Center” (脑网络组研究中心) connectomics project begun in 2013 within the CAS Institute of Automation’s (中科院自动化研究所) “Research Center for Brain-inspired Intelligence (类脑智能研究中心, BII) in Beijing. The authors argue, “many

* IARPA MICrONS program manager David Markowitz reminds us that China’s functional connectomics is, as far as is known, rooted entirely in fMRI.

† The project so far has “netted only modest new scientific insights” as indicated by the absence of papers in top-ranked scientific publications. (Christof Koch, personal communication, July 9, 2020)

current human brain atlases cover only specific structures, lack fine-grained parcellations, and fail to provide functionally important connectivity information." Accordingly:

> "Using noninvasive multimodal neuroimaging techniques, we designed a connectivity-based parcellation framework that identifies the subdivisions of the entire human brain, revealing the in vivo connectivity architecture. The resulting human Brainnetome Atlas, with 210 cortical and 36 subcortical subregions, provides a fine-grained, cross-validated atlas and contains information on both anatomical and functional connections."

The paper describes the methodology used to create the atlas, provides views of its structural parcellation, and instructions on how to display functional relations between brain areas on a publicly accessible website (http://atlas.brainnetome.org). A review of information on the parent organization's (BII) site shows work proceeding on the macro-, meso-, and micro-scales.[36]

5. "Neuroscience and Brain-inspired Artificial Intelligence: Challenges and Opportunities" (神经科学和类脑人工智能发展：机遇与挑战). Han Xue (韩雪), Ruan Meihua (阮梅花), Wang Huiyuan (王慧媛), Yuan Tianwei (袁天蔚), Wang Chaonan (王超男), Fu Lu (傅璐), Chen Jing (陈静), Wang Xiaoli (王小理), Xiong Yan (熊燕), Zhang Xu (张旭) in *Chinese Bulletin of Life Sciences*, 28.11, November 2016, 1295-1307.

This is a clarion call from top scholars in the Shanghai-area neuroscience institutes. The paper celebrates the inclusion of BI-AI in China's top-down planning, alerts the country to analogous projects abroad, and urges further state support for AI-brain fusion in China.

Its authors cite five statutory measures (see Section 4)—from the State Council's "Outline of the National Medium- and Long-term Scientific and Technological Development Plan (2006-2020)" to the 2016 "National Plan for Scientific and Technological Innovation"—which "lay out the development of neuroscience [in China], and have made brain science and brain-inspired research major scientific and technological innovation projects."

They anticipate "major breakthroughs in brain-like computers and brain-inspired artificial intelligence" by 2025. "Meanwhile, a strong working mechanism should be set up and a big brain science program should be planned and implemented efficiently."

6. “China Brain Project: Basic Neuroscience, Brain Diseases, and Brain-inspired Computing” (全面解读中国脑计划：从基础神经科学到脑启发计算).[37] Pu Muming (蒲慕明), Du Jiulin (杜久林), Nancy Y. Ip (叶玉如), Xiong Zhiqi (熊志奇), Xu Bo (徐波), Tan Tieniu (谭铁牛) in *Neuron* 92.3, November 2016.

This paper by several of China’s leading BI-AI/connectomics scientists lays out the paramount role played by the new hybrid discipline in China’s overall “Brain Project.”[38] The paper, in our view, evidences a consummate understanding of the field and its challenges.

It begins with a core assumption that “brain-inspired computing methods and systems are essential to achieve stronger artificial intelligence (AI) and to harness the ever-increasing amount of information.” While acknowledging worldwide progress in brain science on the macroscopic and microscopic levels, it laments an “enormous gap in our knowledge at the mesoscopic [intermediate] level.”[39] Accordingly, detailed information is needed “on the architecture of neural circuits at single-cell resolution and on the spatio-temporal pattern of neuronal activity,” i.e., the “spiking” component absent in earlier ML models. The goal, as the authors see it, is to “dissect neural circuit mechanisms underlying brain cognition and behaviors.” Optimistically, “mesoscopic mapping of neural circuits and their activity patterns” will happen within the next two decades, along with “the underlying logic and mechanisms of cognitive processes.”

China’s Brain Project, in their view, will impact AI in several ways.

- Structurally, the brain’s different types of neurons, synapse stabilization and pruning, the neocortex’s layered composition, and “feedforward and feedback connections within and among brain regions” will provide insight into designs for NNs.
- Functionally, spike coding, synaptic variety and plasticity, short-term memory to long-term memory conversion rules, and “integration of information processing at different levels” will suggest “operational principles for designing efficient” AI.

Another target is machine learning, which (in 2016 and today) “tends to pursue brute-force optimization of a cost function, often using simple and relatively uniform initial architecture.” It is both labor intensive (“labeled data are needed to tune the huge number of parameters”) and costly to run, requiring “high throughput data for training and running [today’s] AI systems.” By contrast, China will research alternative brain-inspired “infrastructures” such as neuromorphic chips and modeling the brain’s ability to combine *computation and storage*. Other designs may simulate cortical columns, brain regions, and neural pathways between brain regions “to achieve efficiency and high throughput in information processing." In sum, BI-AI "systems are expected to exhibit stronger intelligence with less training data or even with unsupervised learning."

Other areas of research described in the paper align with wish list items in Box 3 above, namely, categorization, concept formation, decision-making, "cognition of self and non-self, empathy, and theory of mind." Two citations lay bare the project's ultimate aim (our italics):

- "Learning from information processing mechanisms of the brain is clearly a promising way forward in building stronger and *more general machine intelligence* (通用的机器智能)."
- "The goal is to simulate in principle the mechanisms and architecture of the brain at multiple levels to meet the grand challenge of *making a general AI* (更具有普遍性的AI) that is capable of multitasking, learning, and self-adapting."

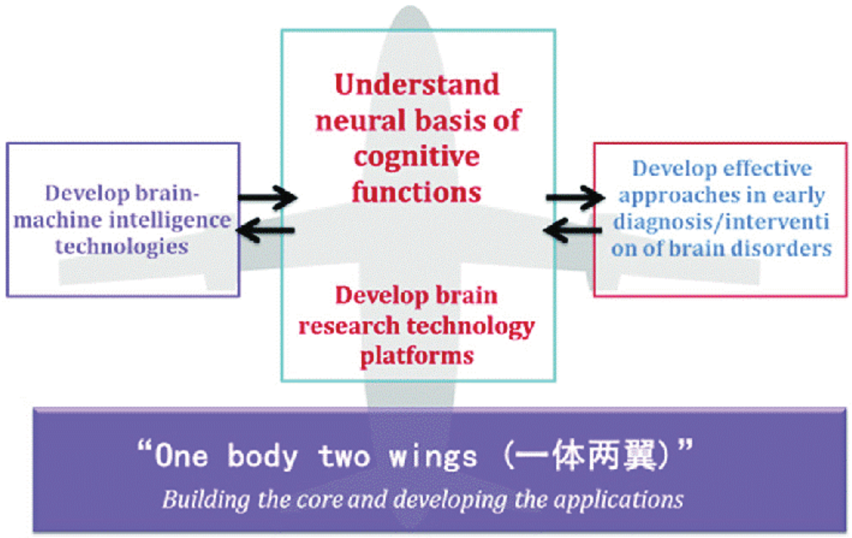
Six more papers round out, and update, our characterization of China's AI-brain "fusion" enterprise.

7. "The Strategic Option of Neuroscience and Brain-inspired Artificial Intelligence in China: Based on a Hundred Experts' Insights" (神经科学和类脑人工智能发展：未来路径与中国布局—基于业界百位专家调研访谈). Ruan Meihua (阮梅花), Yuan Tianwei (袁天蔚), Wang Huiyuan (王慧媛), Wang Chaonan (王超男), Fu Lu (傅璐), Chen Jing (陈静), Han Xue (韩雪), Wang Xiaoli (王小理), Xiong Yan (熊燕), Yu Jianrong (于建荣), Zhang Xu (张旭) in *Chinese Bulletin of Life Sciences* (生命科学) 29.2, February 2017.

The authors claim to have consulted "over a hundred experts" on a "roadmap" for Chinese neuroscience and brain-inspired AI. The results of their inquiry are captured in a proposed "3 + 2 + 2" model for brain science, brain-inspired research, and AI, namely:

- Three key directions—basic neurobiology, neuropsychiatric diseases, and brain-like artificial intelligence;
- Two major supporting areas—transformative neuroscience technology and supporting platforms;
- Two major industries—neurobiological pharmaceuticals / biomedical engineering, and the artificial intelligence industry.

The first of these three points is characterized by the following schematic, widely publicized now in policy papers and on AI-brain related websites:



A proposed "implementation path" (实施路线), defined as follows, suggests that China's AI-brain project in 2017 was already transitioning from consensus-building to realization:

- Integration and docking* of five major systems: China's ministries link up their major projects; local projects are meshed with state-led initiatives; military-civilian equities are adjudicated; state funds are combined with enterprise investment, and the whole of it is integrated with other large-scale plans.
- An overall management structure is built with multi-faceted participation and centralized coordination, a "Neuroscience and Artificial Intelligence Development Leading Group" is created, and an "overseas expert participation mechanism is established."
- "The government and enterprise cooperation mechanism invites experts in sociology and industrial applications to carry out" the recommended roadmap (above).

8. "Looking Back on the Research and Development Hotspots of Brain-computer Interfaces in 2017" (2017 年脑机接口研发热点回眸). Zhang Dan (张丹), Chen Jingjing (陈菁菁), Wang Yijun (王毅军) in *Science and Technology Review* (科技导报), January 2018.

* "Docking" (对接) is a synonym for "linking up" used commonly in China's S&T policymaking circles.

The paper reviews significant worldwide developments in BCI for the preceding (2017) year comprehensively, concisely, and professionally. Chinese innovations that made the cut include: tapping into user "imaginative movement tasks" for better writing performance, at Shanghai's East China University of Science and Technology (華東理工大學); production of a standard data set for steady-state visually-evoked potentials (SSVEP, electrical activity generated by the brain in response to visual stimulation at certain frequencies) with 40 stimulation frequencies (Tsinghua and CAS Institute of Semiconductors); and, at the same CAS institute, "the fastest reported scalp-brain computer interface systems (6.3 bits/second), which is expected to promote the application of BCI in the daily life of ordinary healthy people."†

A second paper the following year[40] reported improved BCI transmission rates. It affirmed the importance of artificial intelligence in BCI: "Deep learning has great potential in brain-computer interfaces, and it is expected to become an effective method for encoding complex signals from sensory systems or implanted electrode arrays, thereby promoting the development of intelligent brain-computer interfaces." Lack of data is a problem that China is working to address.

9. "Current Situation and Prospect of the Basic Translational Application of Brain and Brain-inspired Intelligence in Shanghai" (上海市脑与类脑智能基础转化应用研究的现状及展望). Xie Xiaohua (谢小华), Feng Jianfeng (冯建峰) in *Psychological Communications* (心理学通讯), February 2019.

The authors acknowledge China's late start in brain and brain-inspired research but argue that Shanghai, and its Zhangjiang facilities particularly (see C.6 below), are closing the gap in theory and practical application. They regard brain-inspired AI systems as a "core breakthrough point for next generation AI (下一代人工智能的核心突破点)," and propose a "one two three project" (一二三工程) aimed at insuring the Shanghai area's predominance in the field, namely: "one infrastructure" (the Zhangjiang facilities), "two core capabilities (brain-inspired algorithms and chips), and three key areas of support (brain disease, robotics, intelligent decision-making)."

Co-author Feng's position as Dean of Fudan University's Institute of Brain-inspired Intelligence Science and Technology lends credence to the paper's description of research. Its title suggests a focus on practical applications (转化, "conversion, transformation") and examples are given in the medical fields and robotics especially. Of greater relevance, in our view, given China's historic weakness in

† The "non-primary" BCI discussed in Section 1 above.

theory-driven science[41] is the attention paid here to cutting edge research, exemplified in the following project goals:

- Establish a brain-like intelligence theory system that combines mathematical and biological foundations.
- Establish brain measurement specifications and data standards, mesoscopic-scale data assimilation methods, and multi-scale brain network computing simulation models.
- Develop new modular learning algorithms, and a multi-source, heterogeneous big data theory of intelligence (多源性与异构性大数据智能理论).

10. "Brain-like Machine: Thought and Architecture" (类脑机的思想与体系结构综述). Huang Tiejun (黄铁军), Yu Zhaofei (余肇飞), Liu Yijun (刘怡俊) in *Journal of Computer Research and Development* (计算机研究与发展) 56(6), June 2019, 1135-1148.

The paper reviews past and current worldwide developments in brain-like computing[42] as evidence for its argument that brain-inspired computing and architecture, implementing spiking neural networks, will lead over the next 20 years to "machines with structure close to the brain and performance far beyond the brain."

China's developments "got off to a relatively late start" (起步较晚), but over the past few years have "achieved breakthroughs and large-scale applications." Its authors regard September 1, 2015 as the start of China's official (正式, "formal") involvement when the Beijing Municipal S&T Commission released a "Beijing Brain Science Research" plan consisting of two parts: "brain cognition and brain medicine" (脑认知与脑医学) and "brain cognition and brain-inspired computing" (脑认知与类脑计算). The formulation precedes and—we speculate—was a model for, the "one body two wings" (一体两翼) formula shown in the schematic above.

11. "The Three Development Directions of Brain Science Research" (脑科学研究的三大发展方向). Pu Muming (蒲慕明) in *Bulletin of the Chinese Academic of Sciences* (中国科学院院刊) 34.7, July 2019, 807-813.

Author Pu Muming (Mu-ming Poo) repeats the common—and likely valid—comparison of today's brain science with what was known of physics at the beginning of the 20th century, i.e., not much. He outlines three lines of research that will move brain science and related disciplines forward—an affirmation by China's foremost expert of the "one body two wings" formula. Of the three, two are restatements of the BI-AI / connectomics enterprise.

The project's "main structure" (一体) is the neural basis of the brain's cognitive function. "We hope to launch an international large-scale scientific project *led by Chinese scientists* (our italics) to make a neural connection map at the whole-brain (mesoscopic) level." Treatment of brain disease constitutes one of the "wings" (翼); BI-AI is the other, in his words, "brain-inspired artificial intelligence, brain-inspired computing, and brain-computer interfaces. Research in this area will have a significant impact on the future artificial intelligence industry."

12. "Miniaturized Design of Implantable Brain-computer Interface System" (面向植入式脑机接口系统的微型化设计). Liu Zhaoxu (刘朝旭), Wang Minghao (王明浩), Guo Zhejun (郭哲俊), Wang Xiaolin (王晓林), Liu Jingquan (刘景全) in *Transducer and Microsystem Technologies* (传感器于微系统), September 2019.

The paper describes a complete and portable BCI that works with implanted "neural signal acquisition modules." Experimental results "show that the single-channel sampling frequency of the designed 16-channel brain-computer interface can be as high as 20 kHz, the sampling accuracy is 16 bits, and the system input noise ... is close to the performance of mainstream [stationary] acquisition equipment."

The study was one of 79 Chinese language technical papers in 2019 focused on BCI that we retrieved from a database of peer-reviewed academic journal articles.[43] Other titles investigated the application to BCI of AI concepts (Sections 1 and 2 above) such as deep learning, sparse representation, convolutional neural networks, functional network connectivity, and cognitive computing. In 2019, the popular scientific literature heralded Tianjin University's development of a "Brain Talker" (脑语者) chip allegedly able to separate signal from noise with greater levels of accuracy.[44] The development aims to "replace traditional computer devices used in BCI due to its more portable size, precision in decoding, high efficiency in computing and faster communication ability."[45]

Other recent pronouncements by leading figures underscore these observations. Pu Muming, in a statement reminiscent of Silicon Valley entrepreneur Kai-Fu Lee's assessment of China's AI development,[46] states:

> "Very little pioneering work in AI technology development in the past was done in China, and current AI research in China remains largely focused on the application or incremental modification of existing technologies. The Chinese government has approved the funding of a major 2030 Science and Technology Project on 'Brain Science and Brain-Inspired Technology' (also known as 'China Brain Project'), aiming in part to apply neuroscience knowledge for the

> *development of next-generation AI with human-like intelligence and brain–machine interface technology*. Thus we expect an accelerated development of brain-inspired AI technology in China in the coming decade."[47]

Pu reiterates his justification of the enterprise: "*If the ultimate goal of AI is to achieve human intelligence*, then it would be useful to introduce structural and operational principles of the brain into the design of computing algorithms and devices."[48] (our italics)

Zhang Xu and seven other Shanghai area BI/connectomics researchers also reference the 2016 launch of China's Brain Science and Brain-Inspired Technology project as a game-changer for China AI, noting as does Pu:

> "Using the functional connectome big data, computational neuroscientists will build theoretical models of perception and cognition, to *establish a basis for developing a simulated brain, and the corresponding AI algorithms and hardware*.[49] (our italics)

This review of primarily macro-level, policy-oriented papers offers a window into Chinese scientists' understanding of AI-brain dynamics, its role in China's S&T development, and overall research directions. Technical papers, which number in the thousands, are examined statistically in a literature survey (Section 8) below. The following section details official and institutional support for the scientists' "next generation AI" aspirations.

4 Leadership, statutory, and budgetary support

China's transition to "next-generation artificial intelligence"—in particular, AI inspired by and linked to the human brain—is supported by a host of government statutes and policies. It is hard to find a more explicit endorsement of a scientific paradigm by a nation-state.

The earliest appearance of "artificial intelligence" (人工智能) in a ministry-level notification is the July 1, 2015 "State Council Guiding Opinions on Positively Promoting 'Internet +' Activity" (No. 40), [50] wherein "AI and other technologies" are promoted as components of, or catalysts for, commercial products. The following year a supplement to the notice was issued by a consortium of ministries elaborating on the role AI would play in nine areas of application.[51]

Similarly, on July 28, 2016, a "State Council Notification on National Science and Technology Innovation Programs for the 13th Five-Year Plan," (No. 43) was issued.[52] The document is relevant mostly for what it does *not* emphasize: although AI is mentioned, it is not included among the six major S&T or nine major engineering projects (项目). What appears instead is "brain science and brain-inspired research," listed in the fourth position of importance, defined in the document as "brain-inspired computing" (类脑计算) and "brain-computer intelligence" (脑机智能). In other words, China identified the nexus between "wet" and machine intelligence as a topic for concentrated research *before* designating AI as a priority research area.[53]

By the end of the year, it was clear the Chinese government was moving toward acceptance of AI as a discipline in its own right. On November 29, 2016, the State Council released another notification related to the

13th Five-Year Plan, this time for "National Strategic Emerging Industry Development Projects" (No. 67).[54] Among 21 projects listed, the fifth called specifically for "innovative engineering in artificial intelligence," in particular:

> "Promote basic theoretical research and core technology development, realize the commercialization of neuromorphic computing chips, intelligent robots and intelligent application systems, embed new artificial intelligence technologies in various fields."[55]

The defining document for China's AI program was issued by the State Council on July 8, 2017, titled "The New Generation AI Development Plan" (No. 35).[56] It describes a three-step project to: "synchronize" (同步) AI technology and applications with the world's advanced levels by 2020; make breakthroughs in basic AI theory with some technology and applications reaching world-leading levels by 2025; and lead the world in AI theory, technology, and applications by 2030, a decade from now.[57] More on this later.

Meanwhile, predating these AI-specific measures were China's "National Medium- and Long-term S&T Development Plan (2006-2020)"[58] issued by the State Council on February 9, 2006, which counted "brain science and cognition (脑科学与认知) in its top eight basic research topics; the "12th Five-Year Plan for National S&T Development[59] issued July 14, 2011, which listed "brain science and cognitive science" (脑科学与认知科学) as "important research" topics; and the Shanghai city government's May 27, 2015 "Opinions on Accelerating the Construction of an S&T Innovation Center with Global Influence,"[60] which put "brain science and artificial intelligence" (脑科学与人工智能), i.e., the composite term,[61] among its "first order priorities."

Just as 2016 witnessed the emergence in China of several key BI-AI / connectomics / BCI-related publications (see Section 3 above), so too did it mark the appearance of new statutory measures establishing these disciplines as priority areas of research. The China Brain Project (中国脑计划), a 15-year project approved in March 2016 as part of the 13th Five-Year Plan (2016-2020), "prioritized brain-inspired AI over other approaches."[62] The July 2016 State Council "Notification" (通知) of the five-year S&T plan elaborates on "brain science and brain-inspired research" as follows:

> "With the brain's cognitive principles forming its main body, and brain-inspired computing and brain-computer intelligence, and the diagnosis and treatment of major brain diseases as its two wings, build key technology platforms to seize the commanding heights of frontier research in brain science."

On May 30, 2016, PRC president Xi Jinping himself in a speech to a Ministry of Science and Technology-sponsored assembly of scientists titled "Striving to Build a World S&T Superpower" made the following reference to brain science research in China:

> "Connectomics is at the scientific forefront for understanding brain function and further exploring the nature of consciousness. Exploration in this area not only has important scientific significance, but also has a guiding role in the prevention and treatment of brain disease and the development of intelligent technology."[63]

Two landmark pronouncements the following year (2017) heralded China's commitment to integrate brain research into its AI program—or, in chronological terms, the converse.

The goal of China's "New Generation AI Development Plan"[64] as stated in its introductory paragraph, is to "build for China a *first-mover advantage* in artificial intelligence development."[65] A few lines later, under Strategic Situation, "brain science research" and "brain intelligence" are named specifically as key elements of China's AI program. The word "brain" (脑) itself appears 27 times and "brain-inspired/neuromorphic" (类脑) 20 times in this foundational AI document.

Among the plan's "strategic goals" are to create within the present decade "major breakthroughs in brain-inspired intelligence, autonomous intelligence, mixed [human-artificial] intelligence, swarm intelligence, and other areas so as to have an important impact in the area of international AI research, and occupy the commanding heights of AI technology." More specifically:

> "Brain-like intelligent computing theory focuses on breakthroughs in brain-like information coding, processing, memory, learning, and reasoning theories; on forming brain-like complex systems, brain-like control, and other theories and methods; and on establishing new models of large-scale brain-like intelligent computing and brain-inspired cognitive computing models."

In terms of priorities, "AI-brain" project areas occupy two of the plan's eight "basic theory" categories, specifically "(3) hybrid enhanced intelligent theory" and "(7) brain intelligent computing theory," defined respectively as:

> "Research on 'human-in-the-loop' hybrid enhanced intelligence, human-computer intelligence symbiosis behavior enhancement and brain-computer collaboration, machine intuitive reasoning and causal models, associative memory models and knowledge evolution methods, hybrid enhanced intelligent learning methods for complex data and tasks, cloud robot collab-

orative computing methods, situational understanding in real-world environments, and human-machine group collaboration."

and

"Research theories and methods of brain-like perception, brain-like learning, brain-like memory mechanisms and computational fusion, brain-like complex systems, and brain-like control."

Most of these priorities address our Box 3 "goals of AI-brain research," created independently of the Chinese data from international research and literature reviews. Later in the document under "intelligent computing chips and systems" the plan states:

"Focusing on breakthroughs in energy-efficient, reconfigurable brain-like computing chips and brain-like vision sensor technologies with computational imaging capabilities, we shall research and develop high-performance brain-like neural network architectures and hardware systems with autonomous learning capabilities to achieve multimedia-aware information understanding and intelligent growth, brain-like intelligent systems with *common sense reasoning ability*." (our italics).

The "National Natural Science Foundation of China Artificial Intelligence Basic Research Urgent Management Project Guide,"[66] issued on August 2, 2017, solicited proposals for 25 AI projects. Its first section, titled "Frontiers of Artificial Intelligence," outlined three areas of support for AI's "new stage." All are brain-related, but are also targets of mainstream AI: "(1) information processing mechanisms of human cognitive behavior; (2) brain-inspired models and new computing architectures that reflect cognitive function and brain structure; and (3) how to properly test machine intelligence." Ten "research areas" (研究方向) were nominated, most within our understanding of AI-brain fusion:[67]

1. Multi-modal, efficient cross domain perception and augmented intelligence
2. Machine understanding of perception and behavior under uncertain conditions
3. New methods for complex task planning and reasoning
4. Machine learning theory and methods based on new mechanisms (deep reinforcement learning, adversarial learning, brain-like / natural learning)
5. New brain-inspired computing architectures and methods

6. New methods of human-machine hybrid intelligence
7. Chinese semantic computing and deep understanding (machine reading comprehension and Chinese text creation, human-computer dialogue, etc.)
8. New computing devices and chips for artificial intelligence
9. Heterogeneous multi-core parallel processing methods and intelligent computing platforms
10. Machine intelligence test models and evaluation methods

A second section sponsors "combined advances in cognitive psychology, brain science, and other fields to study the intelligent cognition and behavior of intelligent autonomous bodies." A third section on "intelligent decision theory and key technologies for complex manufacturing" funds such projects as:

- Intelligent prediction and self-healing for abnormal operating conditions
- Feature extraction and knowledge discovery based on heterogeneous data
- Optimal decision-making and mutual learning of human-machine cooperation in an uncertain and open environment

Subsequently, in January 2018, the NNSF published its annual "Project Guidelines" (2018 年度国家自然科学基金项目指南), which for the first time identified "artificial intelligence" (人工智能) as an independent category in the funding schema. Here is the semantic breakdown:[68]

CHINA NNSF ARTIFICIAL INTELLIGENCE FUNDING CATEGORIES

F06	AI (人工智能)
F0601	AI fundamentals (人工智能基础)
F0602	machine learning (机器学习)
F0603	machine cognition and pattern recognition (机器感知与模式识别)
F0604	natural language processing (自然语言处理)
F0605	knowledge representation and processing (知识表示与处理)
F0606	intelligent systems and application (智能系统与应用)
F0607	cognitive and neuroscience-inspired AI (认知与神经科学启发的人工智能)

The guidelines also included the foundation's first attempt to amalgamate AI-brain topics under a consistent rubric (F0607 above):

CHINA NNSF ARTIFICIAL INTELLIGENCE FUNDING CATEGORIES

F060701 computational modeling of cognitive mechanisms (基于认知机理的计算模型)

F060702 modeling attention, learning, and memory (脑认知的注意、学习与记忆机制的建模)

F060703 audiovisual perception modeling (视听觉感知模型)

F060704 neural information encoding and decoding (神经信息编码与解码)

F060705 neural system modeling and analysis (神经系统建模与分析)

F060706 neuromorphic engineering (神经形态工程)

F060707 neuromorphic chips (类脑芯片)

F060708 brain-like computing (类脑计算)

F060709 BCI and neural engineering (脑机接口与神经工程)

While this classification scheme provides clues for gauging NNSF's AI-brain research budget, several problems complicate the matter: (1) information (number of grants and total funding per subdivision) is available for "general program" and minor funding types only; the same data are not available by subdivision for "priority" (重点项目) and other larger funding types; (2) some of the projects under the F0607 funding code are retrievable through online search tools,[69] but not all of them; (3) many that are retrievable do not bin into BI-AI, connectomics, or BCI categories; (4) or do not meet the criteria for "strong" BI-AI (see Section 1 above) and are better regarded as "traditional" AI; (5) and some AI-brain projects are funded by NNSF under other disciplines.

Accordingly, a total NNSF budget for China's AI-brain research cannot be calculated with the data available. A full measure of China's expenditures in these areas would also take account of:

- Grants to scientists from other PRC funding organizations, e.g., MOST, MOE, CAS;[70]
- Institution-level funding for intersectional neuroscience and AI research;

- National, provincial, and local government funding for institute construction, outfitting, maintenance, and research;
- Foreign funding, such as the McGovern Institutes (three in Beijing, another in Shenzhen), Microsoft Research Asia, and other in-country operations and joint ventures;
- Private and state-backed Chinese enterprise investment;
- Diaspora contributions in funding, shared research, and services;
- Bang-for-buck adjustments to reflect China's greater per-dollar purchasing power;

and most importantly:

- The unquantifiable advantages realized from state-sponsored technology transfer programs, discussed below (Section 9) and in other studies by the authors,[71] designed to leverage the investments made by competing nations. For many technologies—AI included—a dollar spent on R&D abroad is a dollar spent for China.

Spending comparisons that do not take account of these China-specific elements are at best misleading, and at worst drastically understate actual (effective) "investment" levels.[72] We lay out these facts for consideration by colleagues contemplating further studies.*

*The authors are preparing follow-up investigations that cover aspects of the program that could not be studied here, including a comparison of China's BI and "traditional" AI efforts. Meanwhile, a *very rough* measure of how effort is proportioned between these two overlapping communities can be gleaned from the inventory of scientists identified in our survey (Section 7 below) as "belonging" to the one camp or the other.

5 China centers for AI-brain research

Whereas AI emerged as a standalone discipline in China only recently, brain science—including aspects germane to our inquiry—has been established there for decades.

The Tsinghua University BCI Lab (清华大学脑机接口研究组) began operations in Beijing in 2004.[74] A year later, two national laboratories were launched in the city by China's Ministry of Science and Technology (MOST): the State Key Laboratory of Cognitive Neuroscience and Learning (认知神经科学与学习国家重点实验室) at Beijing Normal University, engaged in connectomics research, and the State Key Laboratory of Brain & Cognitive Science (脑与认知科学国家重点实验室) also called CAS-ION, doing "multi-disciplinary research on the major scientific issues of 'cognitive basic unit' and 'learning and decision'."[75] By contrast, there was only one state key lab for AI in China before 2017, when MOST stood up its State Key Lab of Cognitive Intelligence (认知智能国家重点实验室) under iFlytek's auspices.[76]

Meanwhile, south of the capital region, Shanghai Jiaotong University has been operating a Center for Brain-like Computing and Machine Intelligence (上海交通大学仿脑计算与机器智能研究中心)* also called BCMI Laboratory, since 2002. Besides its BCI projects, the center's "long term mission is to understand the mechanism of intelligent information processing and cognitive process in the brain and develop new type computing structures and algorithms for information technology," including research in "computer vision, speech signal processing, natural language processing, bioinformatics, machine learning and cognitive computing,"[77] all AI-dependent.

*The word 仿脑 ("imitate brain") in the center's name belies its early establishment. Today's term-of-art is 类脑 ("brain-like" or "brain-inspired").

Pu Muming's International Mesoscopic Connectome Project (国际介观连接体项目), situated in Shanghai within the Chinese Academy of Sciences (CAS) Institute of Neuroscience (中国科学院神经科学研究所), has been operating *since November 1999*.[78] The Beijing Key Laboratory of Human-Computer Interaction (人机交互北京市重点实验室) was originally the "CAS Institute of Software, Laboratory of Human-Computer Interaction Technology and Intelligent Information Processing" (中科院软件所人机交互技术与智能信息处理实验室), also established in 1999.

Our point here, beyond establishing the bona fides of China's neuroscience establishment, is to emphasize that the fundamentals of China's "AI-brain" initiative were in place before AI itself took root in the country as an independent discipline. In China, practice has always preceded theoretical inquiry and this is no exception. Here are more examples:

- CAS Institute of Psychology, Key Laboratory of Behavioral Science (中国科学院心理研究所, 中科院行为科学重点实验室), established in 2009 in Beijing, formally certified as a CAS key lab in 2014.[79] The institute is home to Zuo Xinian (左西年), lead author of the authoritative "An open science resource for establishing reliability and reproducibility in functional connectomics"[80] and a world-class expert.

- Tsinghua University's Center for Brain-inspired Computing Research (清华大学类脑计算研究中心), established in 2014. Research includes neural functional/computational theory, neural coding, machine learning algorithms, and chip architecture. The center recently developed a brain-inspired computing chip and software tool chain.[81]

- CAS Institute of Automation, Research Center for Brain-inspired Intelligence (中科院自动化研究所,类脑智能研究中心), established in Beijing in 2015. The center has research groups for Cognitive Brain Modeling, Brain-inspired Information Processing, and Neuro-robotics.[82] Its Brainnetome Center (脑网络组研究中心) studies brain anatomical and functional connectivity at the macro-, meso-, and microscales.[83]

Note that each pre-dates the emergence of dedicated AI research centers in China beginning in 2017.

A final example from Beijing is the Chinese Institute for Brain Research (北京脑科学与类脑研究中心) established in March 2018. CIBR was "strategically deployed" (战略部署) by the city's S&T commission as a "cooperative framework" for Beijing area universities, the PLA Academy of Military Science (军事科学院), and others.[84] Its mission is "responsibility for coordinating research institutes and managing research programs under the guidance of the China Brain Initiative and Beijing Brain Initiative, and making Beijing the world epicenter for neuroscience and brain-inspired computation."[85] CIBR will spend some 184 million RMB (USD 29 million) on the "first five or six research groups." Cost per year at full capacity will be 400 million RMB (USD 56 million).[86]

We look now at Shanghai, the second largest concentration of AI-brain institutes in China.

Fudan University's Institute of Science and Technology for Brain-Inspired Intelligence (复旦大学类脑智能科学与技术研究院), launched in 2015, hosts "centers" for cognitive neuroscience, computational biology, big data biomedical science, biomedical imaging, neural and intelligent engineering, and brain-inspired chips.[87] Run by Feng Jianfeng (see Section 6 below), it boasts the world's largest brain science database, with access to the U.S. Human Connectome Project, England's Biobank, ISTBI's own 10 terabyte holdings,[88] and the "largest number of magnetic resonance imaging devices in Asia" paired with AI algorithms to screen the images.[89]

Early in 2016, the CAS launched a Center for Excellence in Brain Science and Intelligence Technology (中国科学院脑科学与智能技术卓越创新中心, CEBSIT), drawing on "resources from 20 research institutions, including 80 top laboratories" nationwide.[90] The center shares a website with CAS's own Institute of Neuroscience (ION) in Shanghai (above); both are directed by Pu Muming. It has five broad areas of focus: "(1) neural circuit basis of cognitive functions, (2) mechanisms, diagnosis and therapeutic interventions of brain diseases, (3) novel technologies in brain research, (4) brain modeling and intelligence information processing, and (5) brain-inspired devices and systems."[91] Other areas of research listed under "brain-inspired modeling and intelligent information processing" are:

- "whole brain connectomics analysis (全脑联结组分析), multi-sensory mode perception and accurate image recognition, and computational models for speech and semantic comprehension"

Under "brain-inspired devices and system" are:

- "neuron-inspired computing chips, a new generation of neural network computing devices, brain-inspired intelligent robots, and intelligent training and growth environments for human-machine collaboration"[92]

Pu Muming's center in 2018 established a "G60 Brain Intelligence Innovation Park" (G60脑智科创基地) with a $1.5 billion (US) budget as a "national-level development and transformation center of achievements in technologies regarding brain-inspired intelligence." The facility uses cloned monkeys to eliminate variables between laboratory specimens.[93] Information provided by the Shanghai Municipal S&T Committee (上海市科学技术委员会) on July 1, 2020 indicates a "second phase" of funding in the amount of USD 2.85 billion to be expensed by Dec. 2022.[94]

A third such facility is the Shanghai Research Center for Brain Science and Brain-inspired Intelligence (上海脑科学与类脑研究中心)—also called the Shanghai Brain/AI Center—set up in 2018 by CAS and the Shanghai city government.[95] The center is part of the Institute of Brain-Intelligence Technology (BIT), located in Pudong's Zhangjiang Science City. A major research area is "brain-inspired computing based on artificial neural networks." Collaborators include the HUST-Suzhou Institute for Brainsmatics (below), and the CAS Kunming Institute of Zoology.[96]

Similar institutes are spread throughout China. A sample includes:

- Sichuan Institute of Brain Science and Brain-like Intelligence (四川省脑科学与类脑智能研究院), est. 2018 in Chengdu
- Fujian Key Laboratory of Brain-Inspired Computing Technique and Applications, Department of Cognitive Science, School of Informatics, Xiamen University (福建省仿脑智能系统重点实验), est. 2009 in Xiamen
- South China University of Technology, Center for Brain Computer Interfaces and Brain Information Processing (华南理工大学脑机接口与脑信息处理中心), est. 2007 in Guangzhou
- Guangdong-Hong Kong-Macao Greater Bay Area Center for Brain Science and Brain-Inspired Intelligence (粤港澳大湾区脑科学与类脑研究中心), est. 2018 as a consortium of 16 universities and laboratories
- Shenzhen Institutes of Advanced Technology, Brain Cognition and Brain Disease Institute (深圳先进技术研究院,脑认知与脑疾病研究所) est. 2014 in Shenzhen (BI research, functional connectomics)
- Guangdong Key Laboratory of Brain Connectomics (广东省脑连接图谱重点实验室), est. 2018 in Shenzhen
- Zhejiang University School of Brain Science and Brain Medicine (浙江大学脑科学与脑医学学院), est. 2019 in Hangzhou (hybrid intelligence, BCI, brain-inspired computing)
- Hangzhou Dianzi University, International Joint Research Center for Brain-Machine Collaborative Intelligence (杭州电子科技大学脑机协同智能技术国际联合研究中心, est. 2018 in Hangzhou
- Harbin Brain and Brain-inspired Intelligence Research Center (黑龙江省脑科学与类脑智能研究中心), est. 2019 at the Harbin Institute of Technology
- Southeast University of Brain Science and Intelligent Technology (东南大学脑科学与智能技术研究院), est. 2018 in Nanjing

- Shandong University Institute of Brain and Brain-inspired Science (山东大学脑与类脑科学研究院), est. 2017 in Qingdao
- Henan Key Laboratory of Brain Science and Brain-Computer Interface Technology (河南省脑科学与脑机接口技术重点实验室), est. 2017 at Zhengzhou University

Two more institutes stand out for their size and linkages with other facilities and organizations:

The National Engineering Laboratory for Brain-inspired Intelligence Technology and Application (NEL-BITA) (类脑智能技术及应用国家工程实验室), set up in Hefei's University of Science and Technology of China in May 2017. It was jointly established by Fudan University, CAS's Shenyang Institute of Automation, Institute of Microelectronics, Institute of Electronics, Institute of Neuroscience, Microsoft Research Asia, Baidu, iFlytek (科大讯飞), Datatang (数据堂), and the "new generation" Artificial Intelligence Industry Technology Innovation Strategic Alliance (新一代人工智能产业技术创新战略联盟, AITISA). Research priorities are brain cognition and neural computing, brain-inspired multimodal sensing and information processing, brain-inspired chips and systems, quantum artificial intelligence, and brain-inspired intelligent robots.[97]

Finally, there is the HUST-Suzhou Institute for Brainsmatics (华中科技大学苏州脑空间信息研究院) in Suzhou, established in 2016 at Huazhong University of Science and Technology (Wuhan), run by Luo Qingming (Section 6 below), and budgeted at 450 million RMB (USD 63 million) over five years with a staff of 120. Its commitment to mesoscale connectomics is laid out clearly:

> "With Micro-Optical Sectioning Tomography (MOST) serial techniques as its core, and employing high-resolution, high-throughput and large-detection-area 3D micro-optical imaging techniques, the institute will create a high-resolution mammalian brain atlas for the fine morphology and connectivities of neurons, glia, vasculature, and other complex structures in the whole brain."[98]

The institute goes on to state:

> "These activities include, but are not limited to, digital mapping and visualizing of the neuronal/glial/vascular networks, the connectome, projectome and transcriptome of the brain. Based on big data of three-dimensional fine structural and functional imaging of neuron types, neural circuits and networks, neural-glial interfaces, vascular networks, etc. with high tempo-

ral-spatial resolution and specific spatial locations, brainsmatics makes it possible to better decipher brain function in health and disease, and to promote brain-inspired artificial intelligence (BI-AI) by extracting cross-level and multi-scale temporal-spatial characteristics of brain architectural and functional connectivity."[99]

Mapping these 30 institutions* provides a visceral sense of China's commitment to the AI-brain project.

Computing the simple average of the years these institutions were established gives a mean figure of 2013. Statistics provided by CERNET for new AI colleges or research institutes established from 2015, the earliest on record, through 2019 show a mean start-up year of 2017.[100] While the comparison is imperfect, the gap is wide enough to demonstrate a point we have emphasized throughout this paper—namely, that the intersection between brain science and advanced computational algorithms, including ML, occurred earlier in China than the government's focus on AI itself, which has absorbed so much of the world's attention.

*Others exist. Our count excludes facilities engaged in BI-AI / connectomics / BCI only peripherally.

6 Top Chinese researchers, administrators

This segment introduces a sample of top Chinese scientists* associated with the AI-brain project. Candidacy for this "top 20" list is based on institutional leadership, publication records, and subject matter experts' assessment. The list is a starting point for outreach. It demonstrates the caliber of personnel addressing the AI-brain issue in China.

Du Jiulin (杜久林) is Assistant Director of CAS's Institute of Neuroscience (ION), and Deputy Director of CEBSIT and the State Key Laboratory of Neuroscience. He is a winner of the National Outstanding Young Scientist Award, the Hsiang-Tung Chang Outstanding Young Neuroscientist award, and a Ten Thousand Talents Plan[101] selectee. Du earned a Ph.D. from CAS's Shanghai Institute of Physiology in 1998 and did postdoc work at Tokyo University and UC Berkeley. He joined ION in 2006. His research interests are neural mechanisms underlying visuomotor transformation and adaptive behavior, and molecular mechanisms supporting brain vascular development.[102]

Duan Shumin (段树民) is Dean of Zhejiang University's Faculty of Medicine and Pharmaceutical Sciences, where he led the creation of the Chinese Brain Bank. Duan earned a Ph.D. in neuroscience at Kyushu University in 1991 and began postdoc work that year at CAS's Shanghai Brain Research Institute. From 1995 to 1999, he trained at Kyushu University, University of Hawaii, and UC San Francisco. A Hundred Talents selectee, Duan served as principal investigator at Shanghai's ION from 2000 to 2009. He was elected to the CAS in 2007 and The World Academy of Science in 2008.[103]

*We exclude diaspora scientists whose primary affiliations are outside China. International support for China's brain-AI project is reviewed in Section 9 of this paper.

Feng Jianfeng (冯建峰) is chair of the Shanghai National Center for Mathematical Sciences, Dean of ISTBI at Fudan University, and professor at the Centre for Scientific Computing and Computer Science at Warwick University, UK. Feng is a Changjiang Scholar and Thousand Talents selectee. He was awarded the Royal Society Wolfson Research Merit Award in 2011 and has contributed significantly to modeling single neurons and neuronal networks, ML, and causality analysis.[104]

Guo Aike (郭爱克) is head of ION's Laboratory of Learning and Memory, and a research professor at CAS's Institute of Biophysics. His doctorate is from Munich University and he was visiting scholar at the Max Planck Institute 1982–84. Guo was principal researcher for 973 Program projects and currently leads CAS's "Mapping Brain Functional Connections" strategic priority research program. Guo studies the neuronal assembly of Drosophila, the roots of intelligence, and the brain-mind problem.[105]

He Yong (贺永) is Deputy Director of BNU's State Key Lab of Cognitive Neuroscience and Learning, Founding Director the Beijing Key Laboratory of Brain Imaging and Connectomics, and Principal Investigator at IDG/McGovern Institute for Brain Research (BNU). He was a postdoc fellow at McConnell Brain Imaging Center at McGill University 2005–2007 and a Changjiang Distinguished Professor. Currently, he is Associate Editor of *Human Brain Mapping* and on the editorial board of *NeuroImage*. He has been a "highly cited researcher" for four years running with more than 200 publications.[106]

Huang Tiejun (黄铁军) is chair of Peking University's Department of Computer Science, Dean of the Beijing Academy of Artificial Intelligence, and as of 2019, a member of the New Generation Artificial Intelligence Governance Expert Committee. Huang received his Ph.D. in pattern recognition and intelligent systems from HUST in 1998. A Changjiang Scholar, Huang has authored more than 100 journal articles, three books, and holds 16 granted patents. He is on the IEEE Computing Society's advisory board and a member of the National Standardization Technical Committee. His interests are visual information processing, neuromorphic computing, and artificial general intelligence.[107]

Jiang Tianzi (蒋田仔) is Director of CASIA's Brainnetome Center and National Laboratory of Pattern Recognition, and professor of neuroimaging at the University of Queensland's Brain Institute. Jiang is a Changjiang Scholar, Hundred Talents Scholar, 973 Project chief scientist, IEEE Fellow, and Fellow of the American Institute for Medical and Biological Engineering. He serves as Associate Editor of *IEEE Transactions on Cognitive and Developmental Systems*, *Frontiers in Neuroinformatics*, *Neuroscience Bulletin*, and *BMC Neuroscience*. He has authored more than 250 reviewed journal papers in neuroimaging, connectomics, and clinical applications.[108]

Li Yuanqing (李远清) is Dean of South China University of Technology's School of Automation and Director of its Research Center for BCI and Brain Information Processing. Li researched at Japan's RIKEN Brain Science Institute and Singapore's Laboratory for Neural Signal Processing. He is a Changjiang Scholar, IEEE Fellow, and Assistant Editor for *IEEE Transactions of Fuzzy Systems and Human-Machine Systems*. Li published more than 100 journal papers and edited two books. His research involves blind signal processing, sparse representation, ML, BCI, and fMRI data analysis.[109]

Liu Chenglin (刘成林) is Vice President of CAS's Institute of Automation and Director of the National Laboratory of Pattern Recognition. Liu was a postdoc at the Korea Advanced Institute of Science and Technology and Tokyo University, and senior researcher at Hitachi's Central Research Laboratory 1999–2004. He is a Hundred Talents Scholar, Fellow of the IEEE, Chinese Association for Artificial Intelligence, and International Association of Pattern Recognition. Liu has published more than 300 technical papers in journals and conferences.[110]

Luo Minmin (罗敏敏) is an Investigator at the National Institute of Biological Sciences, Beijing, a professor at Tsinghua University, and Director of CIBR in Beijing. He received his Ph.D. in Neuroscience from University of Pennsylvania and did post-doc training under Dr. Larry Katz at the Howard Hughes Medical Institute and Duke University. Luo, a Ten Thousand Talents award recipient (2016) is principal author of some 60 articles in prestigious academic journals.[111]

Luo Qingming (骆清铭) is President of Hainan University, Dean of the Wuhan Optoelectronics National Research Center of HUSTechnology, and founder of the HUST-Suzhou Institute for Brainsmatics. Luo is a Changjiang Scholar and Fellow at the American Institute for Medical and Biological Engineering. His research focuses on multi-scale optical bioimaging and cross-level information integration. He holds 80 patents and has authored more than 200 papers in peer-reviewed journals, including *Science and Nature*. Luo pioneered micro-optical scanning tomography.[112]

Ming Dong (明东) is Dean of Tianjin University Academy of Medical Engineering and Translational Medicine, Director of the Tianjin Key Laboratory of Brain Science and Neuroengineering, and head of its Brain Science and Brain-inspired Research Center, where the world's first brain-computer codec chip (BC3) "Brain Talker" was developed. Ming, a talents plan selectee, has managed six NNSF projects and has more than 80 patents. His research focuses on BCI, neural system cognition, and quantitative EEG calibration. He has published at least 12 peer-reviewed journal articles in the past three years.[113]

Pan Gang (潘刚) is professor at Zhejiang University's College of Computer Science and Technology and vice-director of the State Key Lab of CAD&CG. Pan has a Ph.D. from Zhejiang University and was a visiting scholar at UC Los Angeles in 2007–08 and a talents plan selectee. He is an associate editor of *IEEE Systems Journal, ACM Proceedings of Interactive, Mobile, Wearable and Ubiquitous Technologies*, and *Chinese Journal of Electronics*. Research specialties are AI, pervasive computing, BCI, and computer vision. Pan has 25 patents granted and has authored more than 100 refereed papers.[114]

Pu Muming (蒲慕明), AKA Muming Poo, is founding director of the Institute of Neuroscience and CEBSIT, and head of the Laboratory of Neural Plasticity. Pu is a foreign member of the CAS (he became a PRC citizen in 2018), and a member of the U.S. National Academy of Sciences. He served as chief scientist of the 973 project "Neural Basis of Human Intelligence" in 2011, and chief consultant to CAS's Strategic Priority Research Project on Mapping of Brain in 2012.[115] Pu called BI-AI a "battleground" and believes it will usher in a "new beginning in next-generation AI computing and devices."[116]

Rao Yi (饶毅) is president of Capital Medical University in Beijing, former Dean of Sciences at Peking University, Founding Director of the PKU-IDG/McGovern Institute for Brain Research, and Founding Director of the Chinese Institute for Brain Research in Beijing. His lab investigates molecular and cellular mechanisms underlying behavior and cognition. Rao returned to China as a member of the first group of Thousand Talent recruits,[117] and in 2011 formally renounced his U.S. citizenship.[118]

Shi Luping (施路平) is Director of Tsinghua University's Center for Brain-inspired Computing Research and the Department of Precision Instruments. Shi earned a Ph.D. at Cologne University and was program manager at Singapore's Academy of Science for AI and memory projects before entering Tsinghua as a Thousand Talents Scholar in 2012, when he founded the center. In 2015, he developed the first brain-like computing chip "Tianjic,"[119] and in 2017 wrote software for neuromorphic chips to support automatic mapping and compilation of NN algorithms.[120]

Tan Tieniu (谭铁牛) is Vice-Director of the Chinese Academy of Sciences, Director of CASIA's Center for Research on Intelligent Perception and Computing, a Hundred Talents selectee, and a Fellow of IEEE, The World Academy of Sciences, and the UK Royal Academy of Engineering. Tan received a Ph.D. from Imperial College, London in 1989 and did research at the University of Reading's Computational Vision Group until 1997. He is also deputy chief of the PRC's liaison office in Hong Kong. His work has 35,000 Google Scholar citations.[121]

Xu Bo (徐波) is Director of CAS's Institute of Automation, Associate Director of CEBSIT, and chair of the "Next Generation Artificial Intelligence Strategic Advisory Committee." He also serves as Director of USTC's Department of Automation, Vice-President of the Chinese Information Processing Society, and has led 973 and NNSF projects. Xu has published more than 100 papers in major academic journals and conference proceedings.[122]

Zeng Yi (曾毅) is professor and Deputy Director of CASIA's Research Center for Brain-inspired Intelligence, Deputy Director of the Sino-Swiss Laboratory for Data Intensive Neuroscience, a principal investigator at CEBSIT, and serves on the 2019 New Generation Artificial Intelligence Governance Expert Committee. He currently works on projects related to brain computational modeling and its applications in AI.[123]

Zhang Xu (张旭) is research professor at CAS's Institute of Neuroscience and Vice President of the Shanghai Branch of the CAS. Zhang graduated from the Fourth Military Medical University in Xi'an and received his Ph.D. in neuroscience from the Karolinska Institute in Stockholm. He is an academician of CAS, The World Academy of Sciences, and directs CAST's Neuroscience Direction Forecasting and Technology Roadmap project. Zhang has published some 110 papers in international journals, including Cell and Neuron.[124]

7 Survey of Chinese scientists and project managers

As a supplement to our research, we surveyed PRC scientists directly on their views about China's AI-brain project. Here are the salient points, grouped into seven categories for convenience.

BACKGROUNDS

- Survey respondents were affiliated primarily with Beijing Normal University, Shanghai's Fudan University, and CAS for specialists, and Xidian University, Tsinghua University, CUST in Hefei, and Dalian University of Technology for generalists.
- A majority (three-fourths) of specialists have a neuroscience background, compared to only 12 percent of generalists, who tended to have computer science and/or information science backgrounds. Overall, computer science and neuroscience were the most common.

FUNDING

- The most prevalent source of funding for generalists (79 percent) and specialists (92 percent) alike was the National Natural Science Foundation of China. Universities were second for both samples (average 40 percent). International funding of specialists is nearly nil (4 percent).
- Most researchers (92 percent) expect NNSF funding in the future, followed by 74 percent who expect funding from MOST. Specialists expect future funding from universities at a higher rate than generalists, who look more to private companies for future funding.

METHODOLOGY AND RESPONSE RATE

Our survey was fielded online through Qualtrics between January 5 and March 4, 2020. Responses were recorded anonymously; no identifier was collected to map a response to a respondent.

The survey included 42 questions and was designed in English and translated into Chinese. We sent the survey to two different populations of Chinese researchers: (1) specialists working in the field of brain-inspired AI and (2) generalists whose research areas are in artificial intelligence or neuroscience, but are not specifically BI-AI related. Based on this selection criteria, we identified nearly 850 researchers (390 specialists and 452 generalists).

Among all researchers, the response rate was 5.8 percent. We collected 49 complete responses; 24 from specialists (6.2 percent) and 25 from generalists (5.5 percent). A response rate of this size is expected for an online, international survey.

The survey's timing could have been better. Reminders went out during Chinese Spring Festival break, and the whole of it coincided with the outbreak of the COVID-19 virus. The results of this exploratory survey nonetheless provide valuable insight into the perspectives of Chinese researchers.

CHARACTERIZATION

- Most researchers (86 percent) agreed with our description of BI-AI, connectomics, and BCI as the pillars of AI-brain research, although a smaller proportion of specialists agreed (75 percent compared to 96). Some added neuromorphic computing.
- Researchers were split in their views on the significance of BI-AI: 39 percent saw BI-AI as a normal progression of AI research, 35 percent saw it as "transformational," and 27 percent regarded BI-AI as one of many parallel approaches. More specialists (42 to 28 percent) saw it as transformational.

FOREIGN DEPENDENCIES

- Almost all respondents claimed to work with international scholars on a regular basis. Most (86 percent) studied and/or worked abroad, on average for 1–2 years. *That figure rises to 96 percent for specialists.*
- A large majority of respondents (88 percent) consider foreign collaboration to be important to their research. Specialists were more likely to indicate

foreign collaboration as extremely important (63 percent), while generalists selected somewhat important (48 percent).

BI-AI IMPACT

- Both groups believe BI-AI will have more impact over the next five years than other competing approaches; about 84 percent selected this option. Only 40 percent of the generalists saw neuromorphic computing as having an impact, compared to 79 percent of the specialists.

- A large majority of researchers (90 percent) foresee "extremely significant" impact of next-generation AI on China and the world. Their projections included replacing human labor, accelerating fundamental research, and greater connectedness.

DRIVERS AND OBSTACLES

- About 60 percent of all respondents view academia as the driving force for AI advances. A higher proportion of specialists selected academia and government than generalists, who were split between academia and private sector.

- 92 percent of generalists and specialists agreed that inadequate basic research is an "obstacle" to the success of China's next-generation AI program. Only 16 percent of all respondents regard inadequate funding as a factor.*

AI AND SAFETY

- A majority of researchers (74 percent) think brain-inspired AI will someday lead to AGI. This prediction is more common among specialists (83 percent) than generalists (64 percent). Of those who predicted AGI at all, a majority (63 percent) believe AGI is more than 10 years out.†

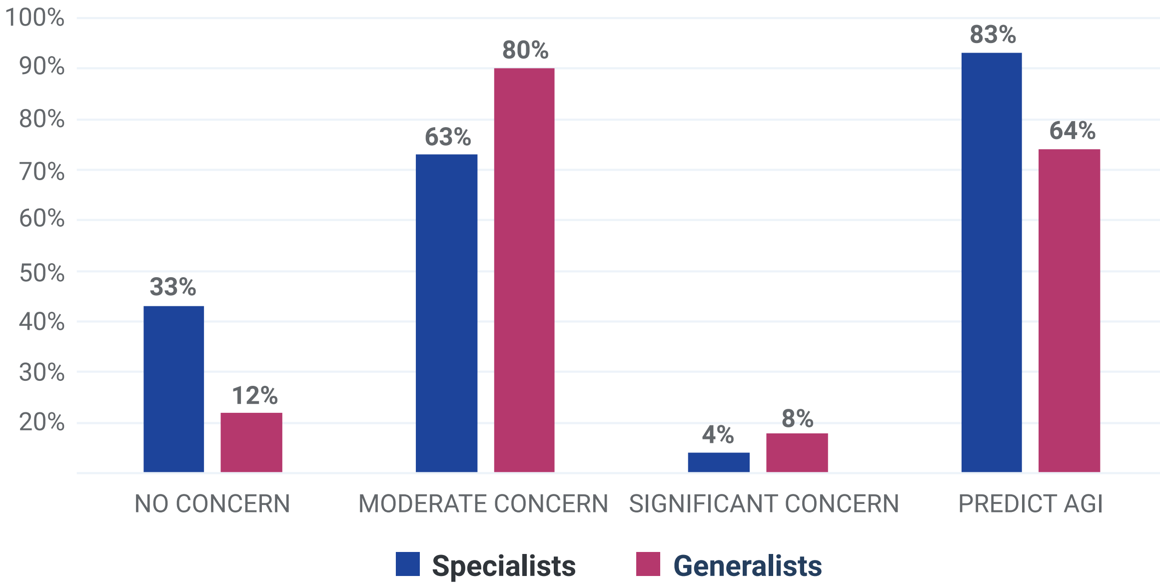
- Researchers agree (96 percent) that international structures and agreements are needed to ensure the safety of next-gen AI. Concern in China for AI safety is "moderate," though *specialists were more likely to suggest there is no concern.* Here is the breakdown:

* Written comments included calls for greater integration of basic and applied BI-AI research in China, to offset the application-driven research that characterizes most Chinese AI development.

† Generalists were 50/50 about whether AGI would be achieved in five to 10 years or 10+ years, while specialists were more aligned that AGI is 10+ years away. This comports with our observation in Section 2 about the sobering effects of hands-on research.

FIGURE 1

Predictions of AGI and AI Safety Concerns in China



Source: CSET survey of China AI scientists.

Respondents' predictions of achieving artificial general intelligence and estimates of the level of concern around AI safety in China. The questions asked "Will brain-inspired AI research lead to artificial general intelligence (AGI), meaning human-equivalent intelligence or better?" and "To your knowledge, what is the general level of concern in China around AI safety?" Respondents had the option to select "don't know."

In sum, we believe the survey agrees with observations made elsewhere in this paper about the status and future of China's AI-brain project, namely:

- BI-AI is likely to have a significant impact on AI in China. In part, this is a self-fulfilling prophecy, since the "new generation" AI program is heavily brain-centric.
- BI-AI in China is more theory-driven than general AI, which responds to commercial demand. That said, researchers agree that basic research gets short shrift in China. We comment on this phenomenon later in the paper.
- Funding for individual researchers is mostly from NNSF, which is some fraction of the total funding. Few respondents see lack of funding as an obstacle, and even fewer depend on foreign funding.

- *Nearly all* respondents have studied or worked abroad, collaborate with international researchers, and consider foreign contact important. We discuss this aspect in Section 9 below.

- Whereas many Chinese scientists believe BI-AI may someday lead to AGI, specialists—who face real problems—are more pessimistic about its prospects. Their lesser concern with AI safety, however, reinforces the need for multilateral safeguards and discussions.

8 China AI-brain publications—content evaluation

This segment presents two types of evaluation of China's AI-brain program based on a Chinese language professional literature review and a subject matter expert's (SME) appraisal.

(1) CNKI-BASED LITERATURE

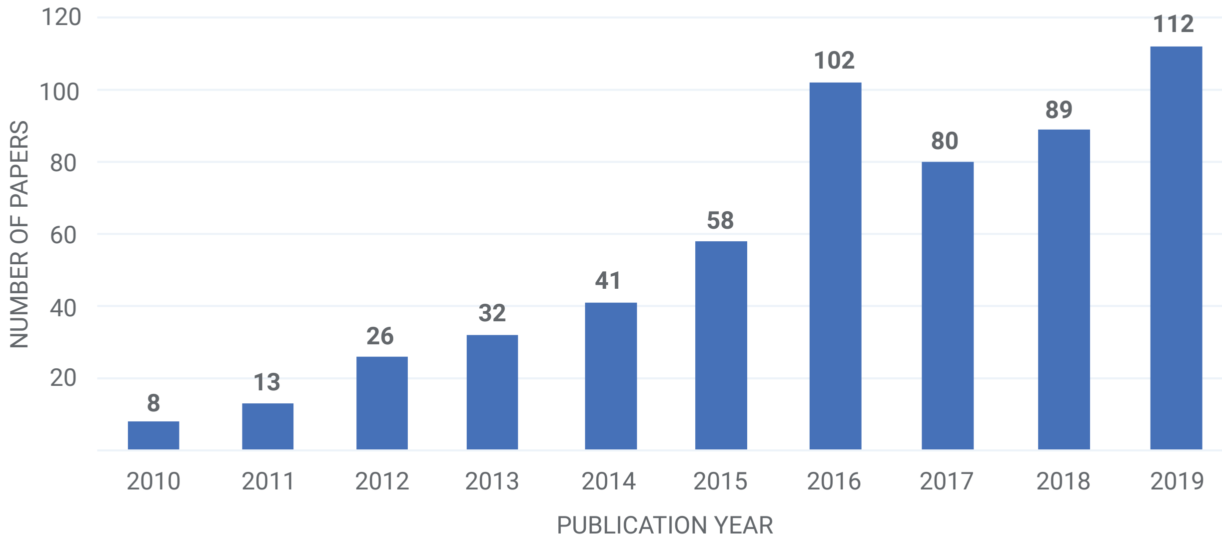
The review was undertaken to determine how Chinese researchers are addressing the AI-brain topic as a whole, and the problems identified in Section 2 above as indicative of a "strong" BI program, i.e., object/scene vision, attention modeling, continual learning, episodic memory, intuitive understanding, imagination, planning, sensemaking, and effective BCI. Neuromorphic computing was added in deference to the views of some survey respondents.

The following three figures show the quantitative progression of a defined class of Chinese language technical journal articles published between 2010 and 2019, whose main author claims a primary China affiliation.* The sets were generated by restricted keyword lists to avoid inflation with peripheral topics. Some 22,000 documents were returned by the initial search. The corpus underwent further selection to eliminate papers that referenced topic areas but did not focus on them specifically and, finally, was hand curated to produce core document sets that could be compared reliably across years—the goal of this exercise.

* All CNKI content furnished as machine-readable data files for off-platform use by East View Information Services, Minneapolis, MN, USA. The corpus did not include (a) papers in English by China-affiliated authors, (b) diaspora papers in either language, (c) papers with China-affiliated (non-primary) co-authors only, or (d) a search for papers by authors in the core set whose output was not fully retrieved by the basic keyword searches—a process that typically doubles the corpus.

FIGURE 2

CKNI Papers Per Year (BI-AI)

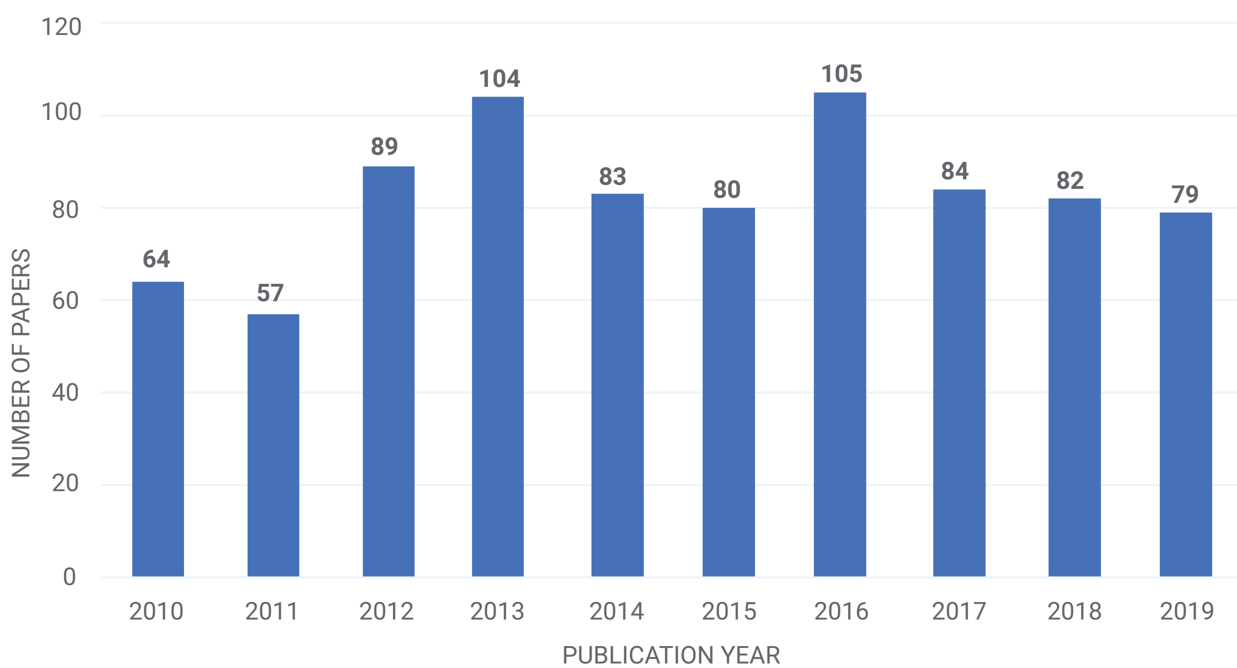


Source: CNKI database of Chinese academic journal articles.

Figure 2 of BI-AI-related publications shows the anticipated spike in 2016 and continued growth to the present as the program gathers steam.

FIGURE 3

CKNI Papers Per Year (Connectomics)



Source: CNKI database of Chinese academic journal articles.

Figure 3 of connectomics is a more level distribution reflecting its earlier arrival as a neuroscience discipline. Although the 2016 peak appears, its subsequent decline is an artifact of the binning process, where increasing identification with BI-AI makes it harder to tag separately.

FIGURE 4

CKNI Papers Per Year (BCI)

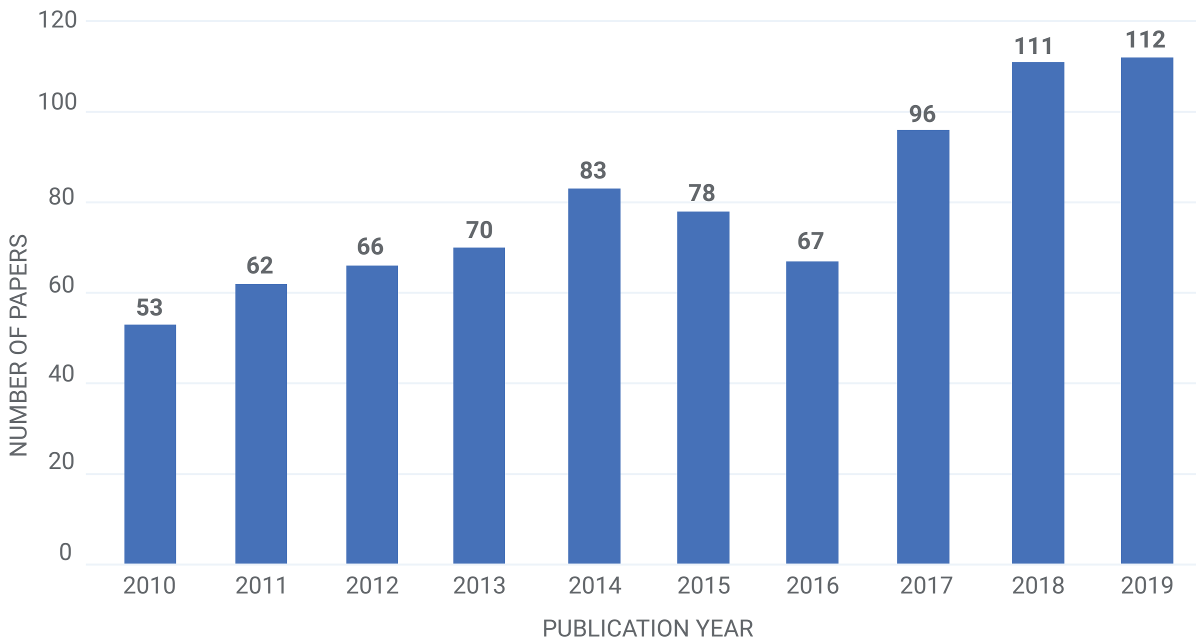
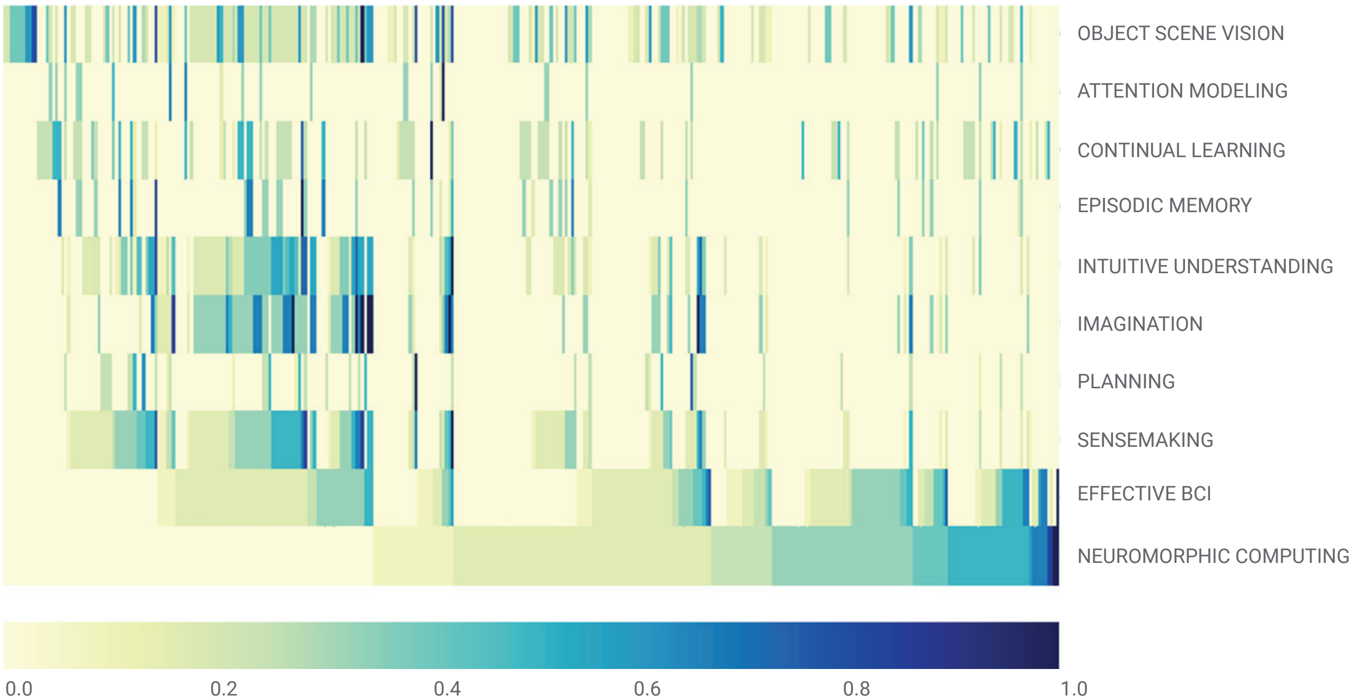


Figure 4 of BCI shows continuous rise. The anomalous drop in 2016, the same year publications in BI-AI and connectomics spiked, may merit further study.

These records support inferences made from other types of information that China has engaged in an accelerated effort since 2016 to "merge" AI and neuroscience. Among the 561 BI-AI related papers published 2010 to 2019 that matched the keywords query, 352 papers can be categorized into one or more of the 10 BI-AI categories identified above (Section 2) as indicative of state-of-the-art research. The following figure—a heat map of 352 Chinese BI-AI technical journal documents—is evidence the project is addressing, or at least appreciates, the problem's "hard" goals.

FIGURE 5



Source: CNKI database of Chinese academic journal articles.

Each of the 352 columns represents a single document of a CNKI corpus,* arranged by affinity to two canonical indicators: "neuromorphic computing" and "object/scene vision" (the choices are arbitrary). The color spectrum of each segment reflects the category affinity of that paper. The figure demonstrates that all categories—albeit some more than others—indicative of a serious BI-AI program by international standards are objects of Chinese research.

(2) SME NARRATIVE APPRAISAL†

1. BI-AI

There was an earnest call to develop brain-inspired research in 2016 and many new research institutes were founded in this namesake. Speaking to the more pro-

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* A refined query returned 561 BI-AI related papers published 2010 to 2019, from which 2,191 keywords were extracted. Each keyword was manually assigned, where possible, to one of the 10 categories. If a keyword was too generic to be assigned a category, it was discarded and the paper itself removed from the inventory. In a rough sense, this expedient alone (352 papers of 561 qualified) establishes that "hard" problems associated with BI-AI are being addressed in China.

† Dr. Jennifer Wang, computational neuroscientist, SETA Contractor at the Defense Advanced Research Projects Agency (DARPA), and consultant to IARPA's MICrONS Project.

vincial institutes, they were happy to take the extra funding in 2016 and continue doing the research they had already been doing. However, there is a core of scientists genuinely interested in BI-AI research, who have kept up the momentum of the initiative. They are mostly computational neuroscientists interested in deriving generalizable computing schemes and data representation principles from brain data. This group coincides with the leadership at the several newly erected institutes in Beijing and Shanghai under the Brain Project. Their activity can be reflected in BI-AI conferences and workshops that have become annual events in Beijing and Shanghai since 2016.

Outside China, these researchers had a presence at the 2019 NeurIPS conference, which shows innovative work is being done. From the many papers submitted to AAAI 2019, it is evident that Chinese researchers are aligned with the rest of the world in terms of trends and benchmarks.

China has emerged a top contender in applicable AI technologies. On the machine learning theoretical front, China is rapidly gaining footing in the BI-AI research community on par with Western institutes, as indicated in part by the quantity of accepted papers at international AI conferences and by cover articles in prominent journals over the last five years. With the vast number of Chinese nationals studying at and contributing to the top AI research institutions in the United States (Carnegie Mellon University, Massachusetts Institute of Technology, Stanford University), China has direct access to the top algorithms in the academic world. Many of these scholars are well positioned to return to China and start their own labs.

2. Connectomics

Whereas most brain projects around the world are using mammalian models, China's model system for connectomics is the larval zebrafish. Zebrafish are relatively transparent creatures, so it is possible to optically record neural data in live fish while obtaining neuroanatomical data, resulting in valuable functional connectomes. These datasets are invaluable, in that one can directly study the live interaction of a group of neurons as they respond to the world. Fish and mammalian neural architectures drastically differ; it is highly likely the principles derived may not apply to humans. But the neural algorithms could still offer more elegant data representation or computational solutions in computer science. Creating a zebrafish connectome is not as resource-intensive as generating a mouse or human brain connectome, so China has not needed to innovate on the hardware front of connectomics.

China is actively developing software and algorithms associated with studying connectomes. To establish connectivity among nodes, 2D neuroanatomy images must be stacked, aligned, and each nanometer scale neural process traced through the sample volume. This need to identify objects and track them through thousands of frames is a generalizable problem in computer vision. Connectomics offers vast controlled image datasets to develop these computational capabilities. Solving these questions for connectomics will also lend powerful tools to analyze satellite and surveillance data.

There are several ongoing challenges to reconstruct neural connectomes, a prominent one being the SNEMI3D challenge. As of April 2020, the CAS Institute of Automation (CASIA) ranks in the top 10 alongside Princeton and MIT on the leaderboard, showing they are invested in this field and are excelling.[125]

3. BCI

Historically, BCI is a field led by the United States, enabled by the drive to rehabilitate handicapped soldiers returning from combat. This domain is all but inactive in Europe, as it has scaled back non-human primate research due to ethical concerns and, with the exception of Switzerland, lacks access to capital markets.[126] This trend has also spread in the United States to a lesser degree. Invasive brain implants for therapeutic use in paralysis, Parkinson's, pain, and depression are mostly developed and used in the United States.

There are few known invasive human studies in China for BCI. The existing ones often originate from military and civilian hospitals and are labeled "rehabilitation studies." China has an active non-invasive BCI community, however, based on EEG, which is inexpensive and safe—but has many limitations in terms of signal quality and remains in its infancy. The annual BCI Robotic challenge (held in Shanghai as part of a robotics conference) consists largely of approaches that depend on decoding EEG signals in real time.

The resources for China to develop BCI in earnest came together with the Brain Project. The neurophysiology model for China's Brain Project is the macaque monkey. They are more closely related to humans evolutionarily and are extremely intelligent. The most cutting-edge BCI work has been conducted on macaque monkeys. The brain initiative expanded primate facilities in and around China to house thousands of macaques and marmoset monkeys. Freedom to conduct neuroscience research on these primates has attracted foreign talent to China.[127]

In sum

China is intent on becoming the world leader in AI and has invested heavily in research in academia and industry. The country is very competitive at worldwide AI competitions. It has state-of-the-art technology in facial recognition and is often in the top five for machine vision challenges. China frequently takes the best working algorithms and develops them to train faster, perform better, or apply them to a brand-new domain. Innovating on the theoretical front of AI takes time because it is tied to basic research. China's political and scientific leaders increasingly recognize

BI-AI as a worthy investment, as they believe this will lead to the next generation of AI. China's ability to apply its burgeoning AI expertise to practical problems, its growing (albeit still modest) investment in neuroscience, and demonstrable intent to make the two fields advance in tandem suggest the AI-brain project will be an abiding feature of China's AI landscape.

9

Foreign dependencies

No description of China's AI-brain project—or any advanced Chinese technology program—is complete without an account of its foreign associations. While dwelling on China's foreign dependencies can distract attention from the country's significant indigenous efforts—an error we have no wish to propagate—neither can this dimension be ignored.

China's appetite for foreign technology and penchant for acquiring it has been described on the one hand as a universal practice engaged in by all nations,[128] as the "greatest transfer of wealth in history" on the other hand,[129] and as a composite of legal, illegal, and extralegal behaviors that defy any simple characterization.[130] What cannot be disputed is the scale of China's use of foreign "models" as a shortcut to technological development, particularly in high-tech areas. This phenomenon has been established beyond doubt by multiple studies.[131]

More recently, the authors examined China's application of these transfer practices to AI development and, perhaps unsurprisingly, found the same pattern of activity.[132] In this segment, we will update these findings, as they apply to the AI-brain project especially.

The key document guiding China's formal efforts to achieve parity with, and eventually surpass, world-class levels of sophistication in AI is the "New Generation AI Development Plan" issued by China's State Council in July 2017. We described (Section 4 above) how this document showcases the role that brain-centric research is expected to play in achieving this outcome. The other outstanding feature of the document, from our perspective, is revealed in Section 4 "Key Tasks," where it calls for "speeding up the introduction of top AI talent and younger AI talent worldwide" to form China's "high ground" (高地) of AI experts. This will be achieved by:

- cooperation and interaction with major AI institutes worldwide;
- the use of "special channels and policies" to recruit top AI "talent";
- the "flexible introduction"[133] of AI talent via projects and consultation;
- coordination with China's foreign talent programs ("Thousand Talents Plan").

This State Council plan was followed later that year by a Ministry of Industry and Information Technology action plan[134] for "full use of bilateral and multilateral international cooperation mechanisms" and "attracting high level AI talent and innovative entrepreneurial talent by various means."* The plan also recommended using the "Thousand Talents" and "Ten Thousand Talents" plans to support staffing goals.

Two other state notifications are germane. The Ministry of Education's (MOE) "AI Innovation Action Plan for Institutes of Higher Education," issued April 2, 2018,[135] mandates "key tasks" that are largely foreign-oriented. They include:

- "Increase international academic exchanges and cooperation. Support the establishment of 111 Project 'foreign intellect bases' (引智基地)."
- "Accelerate the introduction of internationally renowned scholars to join in establishing scientific disciplines and scientific research."
- "Organize high-level international academic AI conferences; promote Chinese scholars to important posts in relevant international academic organizations."

As we shall see, these directives were largely fulfilled for the AI-brain project.

The second document is especially important in light of China's known challenges in basic research. On October 12, 2018, MOST issued its "Project Application Guidelines for S&T Innovation 2030 - 'New Generation Artificial Intelligence' 2018 Major Projects"[136] as a follow up to the 2017 "New Generation" plan. A key feature is that, while applicants are limited to "China mainland-registered R&D institutes, universities, and enterprises," project *leaders* can be foreign scientists (外籍科学家) employed by a Chinese entity or concurrently "by both a foreign and Chinese employer." This provision will resonate with many readers, given the U.S. focus on foreign participation in China's talent programs.[137] It helps explain what award

*以多种方式 ("by various means"): A broader expression of the "flexible introduction" concept and a staple of the transfer rhetoric. It invites participants to exercise personal latitude in facilitating a technology's acquisition.

recipients and "two bases"[138] co-optees do in China, and clarifies the paradox of how a country, perceived as poor at abstract science, can do innovative work that is theory-based.

Examples of the role China's foreign talent plays in its AI-brain program are easy to find, including job solicitations from USTC's NEL-BITA lab; biographic information on famous international scientists recruited to China's service; links to the AI-brain program in the "1000 Talents Magazine" (千人杂志);[139] references to Feng Jianfeng (冯建峰), dean of Fudan University's ISTBI, and Zhang Hongjiang (张宏江), former managing director of Microsoft Advanced Technology Center; and a summary in a CAS bulletin of a brain lab's talent plan inductees (17 of its 32 person staff).[140]

CAS, the progenitor of all China's talent programs,* in 2019 hosted international symposia on non-human primate brain science, connectomics, intelligent robotics, pattern recognition, computational neural modeling, advanced mathematics, brain-inspired AI, and computational intelligence.[141] Its Institute of Automation (CASIA), home of the Brainnetome project, runs joint laboratories with universities in Australia, France, Switzerland, Hong Kong, and Singapore on connectomics, intelligent recognition, and data-intensive neuroscience.[142] Its "Introduction to International Cooperation" page reads:

> "More than 320 of CASIA's R/D staff are annually sent abroad on short-term scientific and technological exchanges. CASIA annually hosts more than 700 overseas guests for scientific visits,† and chairs more than ten international conferences each year. Meanwhile, CASIA has actively worked in partnership with a number of internationally well-known research organizations and worldwide companies."

China's AI-brain labs, institutionally and in their staffing, are tied closely to foreign peer organizations. CAS's partnership with IDG/McGovern in Shenzhen, and McGovern's own partnerships with Peking, Tsinghua, and Beijing Normal universities are one example. The Shenzhen Nell Neuroplasticity Laboratory (深圳内尔神经可塑性实验室) established in 2019 at CAS's Shenzhen Institute of Advanced Technology is another. Many more can be found:

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*CAS's "100 Talents Plan" (百人计划) launched in 1994, 14 years before the Thousand Talents Program.

† A canonical abbreviation for the "Special Fund for Overseas Scholars to Return to China for Short Periods to Work and Lecture" (留学人员短期回国工作讲学专项基金) administered jointly by CAS and the NNSF.

CAS's Center for Excellence in Brain Science and Intelligence Technology, besides its national network of affiliates, is supported by an "international advisory committee" which for 2020–2025 includes 10 distinguished researchers from Caltech, Harvard, Stanford, Collège de France, UCL, and Berlin's Max Planck Institute. Its 2013–2019 slate was no less impressive.[143]

CAS's Institute of Automation, Research Center for Brain-inspired Intelligence has its own advisory committee of 15 experts from the United States, Europe, Canada and Australia, engaged in the U.S. Human Connectome Project and Europe's Human Brain Project.[144]

Fudan University's Institute of Science and Technology for Brain-inspired Intelligence hosts an "interdisciplinary international research team" of 21 professor-researchers, including:

> Nobel laureate Michael Levitt, Brain Prize winner Trevor Robbins and other members of the Royal Academy of Sciences, four members of the U.S. National Academy of Sciences, two Changjiang Scholars,* the chief scientist of China's "973" program,† eight project leaders of key national R&D projects, and "a large number of outstanding overseas young researchers"—in all "more than 130 famous international scholars in brain and brain-inspired research. This is in addition to its research partnerships with some 20 renowned universities and research institutes worldwide."[145]

ISTBI is certified by China's Ministry of Education and State Administration of Foreign Experts Affairs (国家外国专家局)‡ as a "111 Project base" for foreign expert recruitment,[146] along with Xidian University's Joint Laboratory of International Cooperation on Intelligent Perception and Computing (智能感知与计算国际合作联合实验室) in Xi'an, the University of Electronic Science and Technology of China's MOE Key Lab for Neuroinformation (神经信息教育部重点实验室) in Chengdu, East China Normal University's MOE Key Lab of Brain Functional Genomics (脑功能基因组学教育部重点实验室), and BNU's State Key Lab of Cognitive Neuroscience and Learning (认知神经科学与学习国家重点实验室).

We have collected a few dozen other examples of collaborative arrangements between China's AI-brain community and foreign institutions but see no need to belabor the point. Instead, we conclude this segment by pointing to a document

*A high-level Ministry of Education award used, like 1000 Talents, to incentivize foreign "talent" participation.

†Also called the "National Basic Research Program." China's national key R&D program for basic science.

‡ China's premier technology transfer oversight organization, now part of the Ministry of Science and Technology.

issued by China's General Office of the Organization Department of the CPC Central Committee in 2016 (No. 60) titled "Notice on Reference Catalogue for the National Introduction of Overseas High-level Talent" (国家引进海外高层次人才参考目录的通知) that lays out—in order—129 S&T disciplines ("priority directions" 重点方向) targeted for talent plan recruitment. In the first of 10 categories of "frontier basic interdisciplinary science" (前沿基础交叉科学领域), "brain-inspired computing" (类脑计算) is listed third, behind "core mathematics" and "applied mathematics," two areas where China is notoriously weak.[147]

Given China's appetite for foreign technology, ability to acquire it, and the country's storied ingenuity at "re-innovation" (再创新), documentation such as this is probably a better measure of China's prospect for developing a technology than (visible) budget outlays, to the extent the latter can be determined at all.

Conclusion

TRUST, BUT VERIFY*

In 2016, China embarked on an effort to accelerate its pace of AI development by leveraging brain science, publicized as a program to "merge" (混合) AI and neuroscience. Our study, beyond validating the existence of this program as a component of China's AI effort, also determined that the program enjoys support within China's scientific community, is addressing international benchmark challenges, is backed by a plan that balances pragmatic achievements (revenue) with theoretical advances, and is insinuated into China's R&D infrastructure.

Accordingly, we assess China's AI-brain program to be a credible effort that merits respect and cooperation for the following reasons:

- China's quest to marry NS with AI predates its focus on AI itself, and is an established line of research.
- The project enjoys significant policy support, with a clear and consistent emphasis on the "brain" as the bedrock of China's "new generation AI" project.
- There is a coherent national program ("one body, two wings") based on using market demand (medical, therapeutic products) to incentivize cutting-edge research.
- Dedicated infrastructure exists throughout the country, co-located with centers of AI development. Funding mechanisms are exercised at all levels.

* "Доверяй, но проверяй."

- AI-brain research in China is addressing the issues characteristic of a goal-oriented, alternative AI program.
- Key figures within China's scientific establishment embrace the program; foreign "talent" is attracted by competitive salaries, facilities, and operating advantages.
- These advantages include the world's largest supply of non-human primates bred for research, and an ethical framework conducive to experimentation.

The program also merits scrutiny. While we dislike ending every China study on a negative note, it is hard to ignore the potential, long-term challenges to United States and world security that China's AI-brain program presents.

For the record, we assess the likelihood of China achieving artificial general intelligence (AGI) soon as low. Chinese scientists agree with this assessment. The project is in its infancy and there is no indication in the published literature that China has made breakthroughs in key areas.

However, we are less confident over the long term (10+ years) that potentially troublesome aspects of this research—or of AI generally—will not emerge, an assessment that comports with the views of Chinese AI experts. One need not subscribe to an AGI scenario to appreciate that *AI research alone* can entail challenging risks. Here is one scenario, for example, which is plausible over a shorter term—and comes directly from a credible Chinese source:

> "Speaking of the brain-computer interaction of tomorrow, we will move from intelligence [of one type] to intelligence [of another] (从智能而来，到智能而去). The future is not about replacing human beings with artificial intelligence, but making AI a part of human beings through interconnection and interoperability. A blend of human and computer without barriers is the inevitable end of the future."[148]

Our proposal to manage these nascent challenges is *not* an AI "race" for which no provocation can be found in the data surveyed here. Rather, our recommendations are twofold:

1. Chinese scientists agree nearly unanimously (96 percent) on the need for international conventions and safeguards to ensure the safe development of a "next-generation" of artificial intelligence, whether brain-inspired or some other progression of existing research. We believe it incumbent on policymakers worldwide to reward this positive attitude with genuine efforts to achieve win-win solutions, agreeable to all sides, that result in a safer world for everyone.

We have less confidence that political decision-makers in China necessarily share these high levels of safety concern, not for sinister reasons, but simply because science—and arguments based on its subtleties—are not necessarily at the top of their daily agendas. The good news is that many of China's political elite have technical backgrounds and are unlikely to dismiss the arguments of near or former colleagues, who are aware of the compelling need for AI safety.

A useful exercise, accordingly, would be to identify leading Chinese scientists who share these near universal concerns *and* have access to China's political decision-makers—or, at least, have sufficient stature within China's AI and neuroscience communities to compel groundswells of concern among colleagues that filter through to responsible officials.

2. Secondly, we reiterate a point made in an earlier paper on Chinese AI technology transfer,[149] namely, the need for a serious, government-sponsored S&T monitoring program based on open sources that can discern when China's, or anyone's, AI or neuroscience programs approach danger points. Absent a determined (institutionalized) effort to observe developments on a day-to-day basis, much as China does vis-à-vis the rest of the world, we have little confidence the United States can detect game-changing technologies early enough to matter, let alone predict their emergence.

While building trust through multilateral agreements, cooperation and even mutual inspections, the ability to verify our trust through a sustainable open source S&T monitoring apparatus—akin if not comparable to what China has been operating since the 1950s—would ensure that our trust is not misplaced.

Appendix: Keywords for searching CNKI-based literature

The following keywords were used to search CNKI-based literature. Keywords listed below are components of regular expressions case-insensitive search syntax. Sometimes it is necessary to use word fragments ("morphemes") in queries. For example, we use the fragment "connectom" to capture case-insensitive results containing both "Connectomics" and "Connectome."

Figures on BI-AI, Connectomics, and BCI incorporate aggregate statistics compiled from CNKI metadata query results. We excluded results from journals whose names contain these Chinese and English words: economics, social, management, finance, business, accounting, insurance, education, food, forum, global, and mosaic.

BI-AI KEYWORDS

- 类脑智能
- 类脑计算
- 神经网络芯片
- 脉冲神经
- 认知脑?计算
- 类脑信息处理
- neural network chip
- pulse neural
- cognitive comput
- 脑连接组
- connectom
- 生.{1,4}机器学习
- biologically informed machine learning
- biologically realistic machine learning
- machine learning neurofidelity
- 仿生机器学习
- biomimetic machine learning
- 类脑人工智能
- brain-inspired AI
- brain-inspired artificial intelligence
- 类脑机器学习
- 脑.{1,4}机器学习

- brain-inspired machine learning
- neuro-inspired machine learning
- neurally-inspired machine learning
- 长期.{1,4}机器学习
- long-term learning machine learning
- long-term potentiation machine learning
- LTP machine learning
- neurobiological constraint machine learning
- predictive coding machine learning
- predictive modeling machine learning
- 稀疏.{1,4}机器学习
- sparse representation machine learning
- 脉冲.{1,4}机器学习
- spike timing machine learning
- 突触智能
- synaptic intelligence
- 质机器学习
- cortical model machine learning
- 类脑架构
- brain-derived architecture
- brain-inspired architecture
- neuromorphic architecture
- 类脑学习
- brain-inspired learning
- neuromorphic learning
- image segmentation machine vision neuroscience
- large-scale projection mapping brain
- neuroinformatics machine learning
- virtual brain connectomics neuroscience machine learning
- brain simulation neuroscience machine learning
- brain-based communication
- closed-loop brain computer machine interface
- invasive brain computer machine interface
- neuropixel
- deep brain stimulation machine learning

- 脑机接口道德
- 脑机道德
- brain machine interface ethics
- 神经义肢
- neuroprosthetics
- neuro-prosthetics
- noninvasive brain machine interface
- 强化学习脑机接口
- reinforcement learning brain machine interface

CONNECTOMICS KEYWORDS

- 脑连接
- 连接组
- connectom

BCI KEYWORDS

- 脑机接口
- brain[\-]computer interface

Endnotes

1. "From an engineering perspective, what works is ultimately all that matters. For our purposes then, biological plausibility is a guide, not a strict requirement." Demis Hassabis, et al., "Neuroscience-Inspired Artificial Intelligence," *Neuron* 95.2, July 19, 2017.
2. IARPA, "IARPA Seeks Partners in Brain-Inspired AI Initiative," January 22, 2015, www.iarpa.gov/index.php/research-programs/microns.
3. Olaf Sporns, *Discovering the Human Connectome* (Cambridge: The MIT Press, 2012).
4. For example, Google's use of a trained NN to fill in data lost while aligning Drosophila brain slices. Peter H. Li, et al., "Automated Reconstruction of a Serial-Section EM Drosophila Brain with Flood-Filling Networks and Local Realignment," https://www.biorxiv.org/content/biorxiv/early/2019/08/04/605634.full.pdf.
5. Margaret Rouse, "Augmented Intelligence," *WhatIs.com*, February 2019, whatis.techtarget.com/definition/augmented-intelligence.
6. "人机混合智能" (human-machine hybrid intelligence). PRC State Council, "新一代人工智能发展规划" (New Generation Artificial Intelligence Plan), July 8, 2017.
7. "Artificial intelligence (AI)/machine learning (ML) has received great attention for the development of BCI applications to solve difficult problems in several domains... AI/ML has since become the most efficient tool for BCI systems." Larbi Boubchir and Yuling Yan, "Call for Papers. Special Issue 'Advances in Artificial Intelligence and Machine Learning for BCI/BMI'," *Bioengineering*, September 2019, www.mdpi.com/journal/bioengineering/special_issues/AI_BCI.
8. Charles N. Munyon, "Neuroethics of Non-primary Brain Computer Interface: Focus on Potential Military Applications," *Frontiers in Neuroscience*, October 28, 2018.
9. IARPA, "MICrONS Proposers Day Abstracts" (hereafter "MICrONS PDA"): Numeta presentation, https://www.iarpa.gov/index.php/newsroom/iarpa-in-the-news/155-research/current-research/microns. The cortex is a thin layer of neural tissue that covers the outer part of the brain's cerebral hemispheres in mammals, and is responsible for motor function, sensory processing, and high order functions such as language and planning.
10. MICrONS PDA: Tolias presentation.
11. Lab motto. Andreas Tolias Lab, "A Less Artificial Intelligence," https://toliaslab.org.
12. MICrONS PDA: Smith, Huerta, Bashenov presentation.
13. Nand Kishor, "IARPA Project Targets Hidden Algorithms of the Brain," *House of Bots*, June 28, 2017, houseofbots.com/news-detail/712-1-iarpa-project-targets-hidden-algorithms-of-the-brain.
14. Adapted from Nikola Kasabov, *Time-Space, Spiking Neural Networks and Brain-Inspired Artificial Intelligence*, (Berlin: Springer 2019), 228. These theoretical capabilities are constrained by serious limitations on hardware and associated algorithms (Dr. Christof Koch, personal communication, July 9, 2020).
15. Demis Hassabis, et al., "Neuroscience-Inspired Artificial Intelligence," 245-258.
16. Farahani et al., "Application of Graph Theory for Identifying Connectivity Patterns in Human Brain Networks: A Systematic Review," *Frontiers in Neuroscience*, June 6, 2019, frontiersin.org/articles/10.3389/fnins.2019.00585/full.
17. "In 2005, Dr. Olaf Sporns at Indiana University and Dr. Patric Hagmann at Lausanne University Hospital independently and simultaneously suggested the term 'connectome' to refer to a map of the neural connections within the brain. The term was directly inspired by the ongoing effort to sequence the human genetic code—to build a genome." "Connectome," *Wikipedia*, May 5, 2020, https://en.wikipedia.org/wiki/Connectome#Origin_and_usage_of_the_term.

18. The mapping, done originally in 1986, was redone in 2019 using new techniques and discovered some 1,500 synapses missed the first time. Steven J. Cook, et al., "Whole-animal Connectomes of Both Caenorhabditis Elegans Sexes," *Nature* 571, July 3, 2019, 63-71, nature.com/articles/s41586-019-1352-7.
19. Gerald M. Rubin, "Unveiling the Biggest and Most Detailed Map of the Fly Brain Yet," Howard Hughes Medical Institution, January 22, 2020, https://www.hhmi.org/news/unveiling-the-biggest-and-most-detailed-map-of-the-fly-brain-yet.
20. MICrONS PDA: David J. Hamilton presentation. Rebecca Hodge, et al., "Conserved Cell Types with Divergent Features in Human Versus Mouse Cortex," *Nature*, September 2019, https://pubmed.ncbi.nlm.nih.gov/31435019/.
21. Cells that surround, insulate, and support neurons. At least one type of glial cell (astrocytes) is believed to send information to neurons, hence must be accounted for in the connectome. Andrew Koob, "The Root of Thought: What Do Glial Cells Do?," *Scientific American*, October 27, 2009, scientificamerican.com/article/the-root-of-thought-what/.
22. Seung Wook Oh, et al., "A Mesoscale Connectome of the Mouse Brain," Nature, April 2014, https://www.nature.com/articles/nature13186. Julie A. Harris, Stefan Mihalas, et al., "Hierarchical Organization of Cortical and Thalamic Connectivity," *Nature*, October 2019.
23. Christof Koch, personal communication, July 9, 2020.
24. "A connectivity atlas of one post-mortem human brain for the larger axons ... is probably feasible within ten years." Christof Koch, personal communication, July 9, 2020.
25. Eric C. Leuthardt, et al., "Neuroprosthetics," *The Scientist,* November 2014, www.the-scientist.com/features/neuroprosthetics-36510. For a description of DoD spending on BCI for prosthetics see: Newsweek Staff, "Using Brain Signals to Move Prosthetic Limbs," *Newsweek*, September 2, 2007, https://www.newsweek.com/using-brain-signals-move-prosthetic-limbs-100529.
26. Elon Musk (Neuralink), "An Integrated Brain-machine Interface Platform with Thousands of Channels," *bioRxiv*, August 2, 2019, https://www.biorxiv.org/content/10.1101/703801v4.
27. DARPA, "DARPA and the Brain Initiative," https://www.darpa.mil/program/our-research/darpa-and-the-brain-initiative.
28. Ming Dong (明东), "'脑语密码' 破译者" ("Decipherer of 'Brain Language Code'"), *Keji Ribao* (S&T Daily), December 25, 2019, http://m.chinanews.com/wap/detail/zw/gn/2019/12-25/9042386.shtml.
29. One scientist described it as being "like two supercomputers trying to talk to each other using an old 300-baud modem." DARPA Neural Engineering System Design program manager Phillip Alvelda. DARPA, "Bridging the Bio-Electronic Divide," January 19, 2016, https://www.darpa.mil/news-events/2015-01-19.
30. Christof Koch, personal communication, July 9, 2020.
31. Ben Williamson, "Brain Data: Scanning, Scraping and Sculpting the Plastic Learning Brain Through Neurotechnology," *Post Digital Science and Education*, April 2019, 65-86, https://link.springer.com/article/10.1007/s42438-018-0008-5.
32. Larbi Boubchir and Yuling Yan, "Call for Papers. Special Issue 'Advances in Artificial Intelligence and Machine Learning for BCI/BMI'."
33. Jeff Coleman, "Brain Computer Interface with Artificial Intelligence and Reinforcement Learning," *Medium.com Blog*, May 4, 2018, medium.com/@askwhy/brain-computer-interface-with-artificial-intelligence-and-reinforcement-learning-9c94b0454209.
34. E.g., Su Min (苏敏) and Yao Dezhong (尧德中), "脑功能多种成像方式整合技术的研究及其进展" ("Research Progress in the Technique of Integrating Multiple Imaging Modalities in the Functional Brain"), 生物医学工程学杂志 (*Journal of Biomedical Engineering*), 2005(2), 385-388.
35. I.e., it is not Sporns' "human connectome." Olaf Sporns, *Discovering the Human Connectome.*
36. http://bii.ia.ac.cn.
37. The Chinese version of the paper, issued separately, omits "Brain Diseases" from the title. It reads literally: "Comprehensive interpretation of the China Brain Project: from basic neuroscience to brain-inspired computing." The content of the two versions is comparable.
38. The project's formal title is "脑科学与脑启发智能" ("Brain Science and Brain-inspired Intelligence"), reflecting BI-AI's importance in the overall enterprise. Pu Muming et al.'s paper describes it as being "formulated as a 15-year plan (2016–2030), with the first five years coincident with China's 13th five-year plan for national social and economic development."

39. The complaint was echoed as late as 2018 in a briefing by IARPA's "MICrONS" project manager, attended by one of the present authors.
40. Chen Xiaogang (陈小刚), Zhang Dan (张丹), Wang Yijun (王毅军), 2018年脑机接口研发热点回眸 ("Looking Back on the Research and Development Hotspots of Brain-computer Interfaces in 2018"), 科技导报 (*Science and Technology Review*), January 2019.
41. Wm. C. Hannas and Didi Kirsten Tatlow, eds., *China's Quest for Foreign Technology* (London and New York: Routledge, 2020).
42. The paper gives a shout-out to IARPA's MICrONS project: "In March 2016, the American Advanced Research Projects Agency for Intelligence (IARPA) launched the Machine Intelligence from Cortical Networks (MICrONS) program to reverse engineer (反向工程) 1 mm3 of cerebral cortex and use these findings to improve machine learning and artificial intelligence algorithms." A DARPA project is also acknowledged: "In 2007, the IBM Almaden Research Center Cognitive Computing Research Group launched a Systems of Neuromorphic Adaptive Plastic Scalable Electronics, (SyNAPSE) project with the support of the U.S. Defense Advanced Research Projects Agency's (DARPA) research and development of cerebral (大脑) simulation software—a cortical simulator."
43. China National Knowledge Infrastructure (CNKI) database, accessed in January 2020.
44. Liu Qian (刘茜), et al., 脑语者：脑科学时代正在走来 ("Brain Talker: The Era of Brain Science Is Coming"), 光明日报 (*Guangming Daily*), January 18, 2020, http://news.sciencenet.cn/htmlnews/2020/1/434964.shtm.
45. Liang Yu, ed., "China Unveils Brain-computer Interface Chip," *Xinhua*, May 18, 2019, http://www.xinhuanet.com/english/2019-05/18/c_138069590.htm.
46. Lee argues that China—to date—has focused on practical applications of AI, leaving theoretical work to foreign scientists. Kai-Fu Lee, *AI Superpowers: China, Silicon Valley, and the New World Order* (Boston: Houghton Mifflin Harcourt, 2018).
47. Mu-ming Poo, "Towards Brain-inspired Artificial Intelligence," *National Science Review* 5, October 25, 2018.
48. Mu-ming Poo, "Towards Brain-inspired Artificial Intelligence."
49. Zhang Xu, et al., "Brain Science and Technology: Initiatives in the Shanghai and Yangtze River Delta Region," *Nature*, July 2019.
50. PRC State Council, 国务院关于积极推进"互联网+"行动的指导意见 ("State Council Guiding Opinions on Positively Promoting 'Internet +' Activity" No. 40), July 1, 2015.
51. PRC National Development and Reform Commission, Ministry of Science and Technology, Ministry of Industry and Information Technology (MIIT), and the Cyberspace Administration of China, 四部门关于印发《"互联网+"人工智能三年行动实施方案》的通知 ("Three-Year Action Implementation Plan for 'Internet +' Artificial Intelligence"), May 23, 2016.
52. PRC State Council, 国务院关于印发"十三五"国家科技创新规划的通知 ("State Council Notification on National Science and Technology Innovation Programs for the 13th Five-Year Plan"), July 28, 2016.
53. A "draft outline" of the plan presented to the National People's Congress on March 5, 2016, more than four months earlier, listed "brain science and brain-inspired research" as fourth in importance on a list of 100 "national strategic engineering plans" (国家战略的百大工程项目). http://www.xinhuanet.com//politics/2016lh/2016-03/05/c_1118240939.htm.
54. PRC State Council, 国务院关于印发"十三五"国家战略性新兴产业发展规划的通知 ("National Strategic Emerging Industry Development Projects"), November 26, 2016.
55. PRC State Council, "National Strategic Emerging Industry Development Projects."
56. PRC State Council, 国务院关于印发新一代人工智能发展规划的通知 ("New Generation AI Development Plan"), July 8, 2017.
57. Parts adapted from Hannas and Chang, "China's 'Artificial' Intelligence," in Wm. C. Hannas and Didi Kirsten Tatlow, eds., *China's Quest for Foreign Technology*.
58. PRC State Council, 国家中长期科学和技术发展规划纲要(2006-2020年) ("National Medium- and Long-term S&T Development Plan (2006-2020)"), February 9, 2006.
59. PRC State Council, 国家"十二五"科学和技术发展规划 ("12th Five-Year Plan for National S&T Development), July 14, 2011.

60. PRC State Council, 关于加快建设具有全球影响力的科技创新中心的意见 ("Opinions on Accelerating the Construction of an S&T Innovation Center with Global Influence"), May 27, 2015.
61. The contiguous phrase "脑科学与人工智能" generated some 36,500 Google hits in May 2020.
62. Mu-ming Poo, "Towards Brain-inspired Artificial Intelligence."
63. "脑连接图谱研究是认知脑功能并进而探讨意识本质的科学前沿，这方面探索不仅有重要科学意义，而且对脑疾病防治、智能技术发展也具有引导作用." http://www.xinhuanet.com/politics/2016-05/31/c_1118965169.htm.
64. PRC State Council, "New Generation AI Development Plan." Translation by the Foundation for Law and International Affairs, verified by the present authors.
65. "构筑我国人工智能发展的*先发优势*" Our italics. The formulation in another context might be less threatening; here it invokes the self-bootstrapping scenario—a mainstay of the AI ethics literature—of a country with an early AI advantage leveraging its lead beyond the point where other nations can compete.
66. PRC National Natural Science Foundation, 国家自然科学基金人工智能基础研究应急管理项目指南. ("National Natural Science Foundation of China Artificial Intelligence Basic Research Urgent Management Project Guide"), August 2, 2017, http://www.nsfc.gov.cn/publish/portal0/tab452/info69927.htm.
67. PRC National Natural Science Foundation, "National Natural Science Foundation of China Artificial Intelligence Basic Research Urgent Management Project Guide."
68. http://www.research.pku.edu.cn/docs/2018-07/20180702201045167492.pdf.
69. "LetPub Professional SCI Paper Editor" (LetPub专业SCI论文编辑), www.letpub.com.cn.
70. E.g., "Class 'B' Strategic Priority Project" funding for "Brain Cognition and Brain-like Frontier Research" (脑认知与类脑前沿研究升级版B类先导专项). Lu Qi (陆琦),以脑启智 融合慧聚, 中国科学报 (*China S&T Daily*), June 25, 2019, http://www.cas.cn/zkyzs/2019/07/206/cmsm/201907/t20190702_4697801.shtml.
71. Wm. C. Hannas and Huey-Meei Chang, "China's Access to Foreign AI Technology: An Assessment," Center for Security and Emerging Technology, September 2019; and "China's 'Artificial' Intelligence," in Hannas and Tatlow, eds., *China's Quest for Foreign Technology* (2020).
72. Andrew Spear, former USTR China analyst and co-architect of the U.S. government's "Section 301 Investigation" into China's IPR appropriation, refers to the phenomenon as "China's composite innovation system," a framework accepted now by many students of the problem. (see Andrew Spear, "Serve the Motherland while Working Overseas" in Hannas and Tatlow, eds., *China's Quest for Foreign Technology*).
73. http://thubci.org/en/. The lab is complemented by the Tsinghua Laboratory of Brain and Intelligence (清华大学脑与智能实验室) established in 2017.
74. http://brain.bnu.edu.cn/en/Home/.
75. http://bcslab.ibp.cas.cn.
76. Hannas and Chang, "China's Access to Foreign AI Technology: An Assessment," 15.
77. http://bcmi.sjtu.edu.cn/index.html.
78. http://www.ion.ac.cn/. China's International Mesoscopic Connectome Project was launched at the end of the 1990–1999 "Decade of the Brain" announced in July 1989 by former U.S. President Bush, which had given rise to waves of public and private funding and centers created for advanced research on the brain and its functioning.
79. http://www.psych.cas.cn/jgsz/kyxt/xwkx/.
80. Xi-Nian Zuo, et al., "An Open Science Resource for Establishing Reliability and Reproducibility in Functional Connectomics, *Scientific Data*, December 9, 2014, https://www.nature.com/articles/sdata201449.
81. https://www.cbicr.tsinghua.edu.cn.
82. http://bii.ia.ac.cn. The lab is equipped to "model mammalian brains," has achieved successes in "brain-like learning and decision-making on intelligent robots," and claims to have created "the world's first robot that passed mirror tests in a brain-like manner." http://www.xinhuanet.com/science/2018-05/14/c_137178022.htm.
83. http://www.brainnetome.org/.
84. www.cibr.ac.cn/.
85. https://jobs.sciencecareers.org/employer/513965/the-chinese-institute-for-brain-research-beijing-cibr-/.
86. David Cyranoski, "Beijing Launches Pioneering Brain-science Centre," *Nature*, vol. 556, April 12, 2018, https://www.nature.com/articles/d41586-018-04122-3.
87. https://istbi.fudan.edu.cn/.

88. www.ecst.com.cn/topic/detailIndex.html?id=1347.
89. David Cyranoski, "Beijing Launches Pioneering Brain-science Centre."
90. http://www.ion.ac.cn/.
91. http://www.cebs.ac.cn/en/about.php.
92. http://www.cebsit.cas.cn/yjsjj/szzc/.
93. Zhou Wenting, "Insights to Come from New Brain Research Base," *China Daily*, July 19, 2018, http://www.chinadaily.com.cn/cndy/2018-07/19/content_36603871.htm.
94. https://www.cingta.com/detail/17634.
95. https://www.bsbii.cn/.
96. Zhang Xu, et al., "Brain Science and Technology: Initiatives in the Shanghai and Yangtze River Delta Region."
97. https://braindata.bitahub.com/.
98. http://en.jitri.org/yanjiuyuan72.html.
99. http://en.jitri.org/yanjiuyuan72.html.
100. Hannas and Chang, "China's Access to Foreign AI Technology: An Assessment," 20.
101. 万人计划. The MOE's "AI Innovation Action Plan for Institutes of Higher Education" (2018) calls for building "interdisciplinary and cross-disciplinary teams and innovative research groups" from AI, brain science and cognitive science through use of talent programs. http://www.moe.gov.cn/srcsite/A16/s7062/201804/t20180410_332722.html.
102. http://www.cebs.ac.cn/en/duiwu_teacher.php?id=92.
103. https://person.zju.edu.cn/en/0006042#0. https://en.wikipedia.org/wiki/Duan_Shumin.
104. https://istbi.fudan.edu.cn/lnen/info/1157/1629.htm.
105. http://www.cebs.ac.cn/en/duiwu_teacher.php?id=1.
106. http://brain.bnu.edu.cn/a/zh/keyantuandui/jiaoshou_yanjiuyuan/2016/0221/600.html.
107. https://eecs.pku.edu.cn/info/1503/6707.htm. https://ieeexplore.ieee.org/author/37401330100.
108. http://www.nlpr.ia.ac.cn/jiangtz/. https://researchers.uq.edu.au/researcher/2339.
109. http://www.med.tsinghua.edu.cn/SingleServlet?newsId=1345. http://www.2017.ieeeglobalsip.org/sym/17/HCE.html.
110. http://www.nlpr.ia.ac.cn/liucl/#Awards.
111. http://en.cibr.ac.cn/index.php?s=/Show/index/cid/16/id/17.html.
112. http://brainsmatics.org/document.action?docid=69677.
113. http://amt.tju.edu.cn/portal/teachers/getperson/id/40/sId/2/bId/2.html.
114. https://person.zju.edu.cn/en/gpan.
115. http://www.cebs.ac.cn/en/duiwu_teacher.php?id=104.
116. http://www.xinhuanet.com//world/2016-04/28/c_128942147.htm.
117. https://gairdner.org/staff/yi-rao/.
118. Rao, Yi, "My Relatives in Wuhan Survived. My Uncle in New York Did Not," *The New York Times*, July 22, 2020, https://www.nytimes.com/2020/07/22/opinion/coronavirus-china-us.html?_ga=2.228975188.996362065.1595722016-1199988922.1595722016.
119. https://cncc.ccf.org.cn/.
120. https://www.cbicr.tsinghua.edu.cn/shi-luping/.
121. http://cripac.ia.ac.cn/people/wwang/authors/tieniu-tan/; https://baike.baidu.com/item/谭铁牛.
122. http://www.cebs.ac.cn/en/duiwu_teacher.php?id=160.
123. http://bii.ia.ac.cn/~yizeng/.
124. http://www.cebs.ac.cn/en/duiwu_teacher.php?id=91.
125. http://brainiac2.mit.edu/SNEMI3D/leaders-board.
126. Christof Koch, personal communication, July 9, 2020.
127. Gretchen Vogel, "Monkey Facility in China Lures Neuroscientist," *Science* 31, January 2020, 496-497, https://science.sciencemag.org/content/367/6477/496.2. Vogel's complaint reflects the frustration of American and European scientists with restrictions on primate research. China has fewer such obstacles. As he points out, "(T)he acceptance of nonhuman primate research by authorities and the public in China is much higher than in Europe."
128. Declarations to the authors at multiple closed and open U.S. government and academic fora.

129. Keith Alexander, former Director, U.S. National Security Agency. Josh Rogin, "NSA Chief: Cybercrime Constitutes the 'Greatest Transfer of Wealth in History'," *Foreign Policy*, July 9, 2012, https://foreignpolicy.com/2012/07/09/nsa-chief-cybercrime-constitutes-the-greatest-transfer-of-wealth-in-history/.
130. Hannas and Tatlow, eds. *China's Quest for Foreign Technology*.
131. E.g., The IP Commission Report, *The Theft of American Intellectual Property: Reassessments of the Challenge and United States Policy*, February 2019. Wm. C. Hannas, James Mulvenon, and Anna B. Puglisi, *Chinese Industrial Espionage* (London and New York: Routledge, 2013), hereafter "CIE." Michael Brown and Pavneet Singh, *China's Technology Transfer Strategy* (Washington, DC: Defense Innovation Unit Experimental, February 2017). Office of the United States Trade Representative, "Section 301 Report into China's Acts, Policies, and Practices Related to Technology Transfer, Intellectual Property, and Innovation," March 27, 2018. U.S.-China Economic and Security Review Commission, "2019 Annual Report to Congress," November 2019.
132. Hannas and Chang, "China's Access to Foreign AI Technology: An Assessment."
133. 柔性引进: a term of art in the technology transfer literature defined on Baidu as: "Flexible introduction refers to breaking the rigid constraints in the flow of talents such as nationality, household registration, region, identity, archives, personnel relations, etc., and adapting to the requirements of the market economy and the socialization of talents *without changing and affecting the personnel relations between the talents and their affiliates*" (our italics). https://baike.baidu.com/item/柔性引进/6812150. In other words, service China's technical needs without losing access to the (foreign) institutional knowledge base supporting those needs.
134. PRC Ministry of Industry and Information Technology, 促进新一代人工智能产业发展三年行动计划 ("Three-Year Action Plan to Promote the Development of New-Generation AI Industry"), December 14, 2017, Section 4, "Accelerate the Cultivation of Talent."
135. PRC Ministry of Education, 高等学校人工智能创新行动计划 ("AI Innovation Action Plan for Institutes of Higher Education"), April 2, 2018.
136. PRC Ministry of Science and Technology, 科技部关于发布科技创新2030—"新一代人工智能"重大项目2018年度项目申报指南的通知 ("Project Application Guidelines for S&T Innovation 2030 - 'New Generation Artificial Intelligence' 2018 Major Projects"), October 12, 2018, http://www.most.gov.cn/mostinfo/xinxifenlei/fgzc/gfxwj/gfxwj2018/201810/t20181012_142131.htm.
137. See Jeffrey Stoff, "China's talent programs" in Hannas and Tatlow, eds., *China's Quest for Foreign Technology* for an up-to-date account of China's foreign talent recruitment programs.
138. 两个基地: another common term in the Chinese technology transfer lexicon. It refers to a policy launched by China's National Natural Science Foundation in 1992, subsequently reaffirmed, to incentivize overseas scientists to contribute to—or lead—research in China while maintaining a parallel operation abroad. See Hannas et al., CIE, 89, 168, 171-174.
139. http://www.1000thinktank.com/ztbd/26499.jhtml.
140. http://www.bulletin.cas.cn/publish_article/2016/7/20160718.htm.
141. http://www.bic.cas.cn/gjhy/jqgjhylb/201907/P020190725742660780529.pdf.
142. http://english.ia.cas.cn/ic/introduction/.
143. www.cebsit.cas.cn.
144. http://www.ia.cas.cn/kxcb/kpwz/201307/t20130730_3906966.html.
145. http://www.rencai8.com/web/job_content.php?id=34286. https://baike.baidu.com/item/复旦大学类脑智能科学与技术研究院/22704541.
146. The "Project of Introducing Talents of Academic Disciplines to Universities" (高等学校学科创新引智计划), a state-led program to create 100 first-class universities in China by recruiting 1,000 overseas experts from the world's top 100 research institutions. Each "base" is required to hire 10 or more foreign experts. The project over-achieved; by 2018, 412 bases were established. Andrew Spear, "Serve the Motherland While Working Overseas" in Hannas and Tatlow, eds., *China's Quest for Foreign Technology*.
147. https://hr.pku.edu.cn/docs/20170106131009584633.pdf.
148. Ming Dong (see Section 6 above), "Decipherer of 'Brain Language Code'."
149. Hannas and Chang, "China's Access to Foreign AI Technology: An Assessment."