Issue Brief

Bibliometric Analysis of China's Non-Therapeutic Brain-Computer Interface Research

Alternate Paths to Cognitive Augmentation and Control

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Executive Summary

“Brain-computer (or brain-machine) interfaces” are a class of technology that allows direct communication between biological brains and computational resources, without the intervention of speech, tactile input, or the use of other sensory organs. Linkage is achieved through wires or wirelessly to contact points placed on the skull or inside the skull cavity. These interfaces—"BCIs”—have been used mainly to treat cognitive and neurological impairments.

With improvements in related technologies, however, it is now feasible to extend BCIs to the general population, potentially leading to a synthesis between the two types of intelligence—human and machine. This facilitated “merger” of natural and artificial cognition opens a path to a range of applications that could provide strategic advantages to early adopters—a prospect that has not been lost on China.

The present study reviews Chinese papers and patents for evidence of research consistent with the aspirations of Chinese scientists—captured in prior CSET studies—to build toward this state of BCI-enabled cognitive enhancement. A bibliometric analysis of several hundreds of Chinese documents indicates China embraces this goal and has realistic pathways to achieve it. China’s research in non-invasive and invasive BCI is at the world-class level thanks to indigenous work across the spectrum of related disciplines and China’s ability to benchmark foreign designs.

Although collaboration with foreign and, especially, U.S. experts accounts for part of China’s success, the analysis shows that global input to Chinese BCI programs accounts for a small and diminishing volume of the research, as evidenced in co-authorship patterns.

The study begins with an account of its assumptions and methods, followed by details on the institutions and people that our analysis indicates are most likely to achieve breakthroughs in non-therapeutic BCI in China. Medical uses of brain-computer interfaces, while not part of the study’s focus, are cited where needed since they underpin much of China’s BCI research.

Readers short on time can skip the preliminary sections and go directly to “Expert Assessments” for an overview of the paper’s substantive findings, which are: Chinese scientists are researching with measured success a variety of BCI technologies and applications, with an emphasis on signal processing, new materials, and detecting cognitive and emotional states. These efforts are comparable in sophistication to those in the United States and the United Kingdom and position China to achieve a sought-after merger of human and machine intelligence.

This study is a joint effort by analysts at Georgetown University’s Center for Security and Emerging Technology and King’s College London’s Department of War Studies. It is based wholly on Chinese open sources and benefits from insights provided by neuroscience experts. The paper recommends an open-source monitoring program be established to track China’s development of BCIs in the interest of national security and safety.

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Introduction

Prior research by CSET analysts highlighted China's efforts to "merge" human and machine intelligence by leveraging advances in artificial intelligence.[1] This goal, announced in China's 2017 "New Generation AI Development Plan,"[2] is understood in China metaphorically as human-machine interdependence, but also literally, in the sense of building AI that replicates features of human cognition, so that as AI improves, the distinction between the two types of intelligence disappears. There are (at least) three paths to this latter goal and China is pursuing each of them.[3]

- Chinese scientists are modeling the structural and functional neural pathways responsible for cognition, efforts that are "brain-inspired (类脑)" in a strict sense.[4]
- China is also pursuing "traditional" and generative machine learning (ML) aimed at eliciting human-like performance through training on large corpora, the goal being artificial general intelligence (AGI) that mimics or exceeds human cognitive ability.[5]
- Finally, China is leveraging brain-computer interfaces (BCI), originally developed in therapeutics, to augment human cognition and human-machine teaming by linking brains directly to computational resources.[6]

This last path to advanced intelligence is the topic of the present study. While the theoretical outcome of all three approaches—acknowledged by Chinese scientists—are forms of *synthetic intelligence*, or augmented *general intelligence*, brain-computer interfaces may also support *hybrid intelligence*, in which human intentionality drives an increasingly capable synthesis.

BCIs are direct communication paths between biological brains and external devices, typically computers, designed originally for use in treating pathology such as paralysis following a stroke or locked-in syndrome in advanced amyotrophic lateral sclerosis, also commonly known as ALS.[7] Although the technology has been under development since the 1970s, recent advances in materials, placement strategies (based on understanding the neural bases of cognitive function), signal processing techniques and machine learning (ML) have improved their functionality, opening the way to non-therapeutic uses, such as cognitive enhancement and control. BCIs can potentially:

- Enable high-bandwidth connections that exceed conventional interfaces.
- Access private information (such as a person's cognitive and emotional states).
- Directly stimulate neuronal targets and thereby achieve cognitive and physiological states not otherwise possible (e.g., emotion control and alertness).

Other applications range from gaming through decision-making, as well as attention monitoring, mood detection and modification, communications, weapons management, robot control, and ultimately exobrains ("twin brains")[8] and digital immortality.[9]

Hence, BCIs are "dual-use" technologies whose therapeutic origin masks their potential for applications that can confer strategic advantages on states adapting them for scientific research, productivity gains, power projection and political control.[10] These practical applications may be realized well before BCI's arrival as a catalyst for AGI, adding urgency to the need to track their development. There are also ethical challenges to BCI's use that demand attention, ranging from medical risk to privacy and autonomy usurpation at the most basic level.

Earlier CSET work identified through internet research Chinese BCI programs based on non-invasive technology (electrodes placed on the scalp, e.g., using electroencephalography, also known as EEG), where China has an established record and new efforts based on invasive techniques (inside the cranium).[11] The present study looks deeper into China's BCI enterprise with a particular focus on cognitive augmentation, irrespective of placement strategy.[12] Its goals are to evaluate Chinese claims cited in the earlier CSET papers about the course of BCI development there and provide a methodology to track it.

The study begins by describing its sources and methods. Details on China's advanced BCI infrastructure—derived from the metadata associated with patents and peer-reviewed papers—are provided in sections on Chinese institutes, scientists, companies and "global dependencies." The study also assesses the content of these papers and patents. Observations from these data inform a final set of recommendations.

Sources and Methods

The following source types were used in the study:

- BCI conferences in China and abroad
- China academic departments, laboratory websites
- China company websites, press releases
- Chinese and English-language academic journal articles
- Google and Baidu search strings
- Patents databases
- PRC ministry sites and state labs
- Subscribed database feeds (U.S. and UK)
- Technical books by Chinese publishers

Data collection began by defining two complementary approaches: (1) *keyword searches* on the internet (for web-based information), on proprietary data holdings (for patents and academic studies), and (2) *incubators*—some 20 organizations and 50 persons known from prior research[13] to be involved in the targeted activity, whose work and biographic data are publicly accessible.

Keyword choices straddled the gap between too broad and too narrow. Internet searches on “BCI,” or “脑机接口 / brain-computer interface,” yielded millions of results, even when paired with “中国 / China.” Narrower exotic terms such as “神经元逐步替换 / gradual neuron replacement” and “心灵上传/ mind uploading” gave manageable numbers but bypassed useful data. The upshot was a search strategy that combined generic with focused terms,[14] for example, “脑机接口 (BCI)” plus “信息高速公路 (high-speed information highway),” to discover relevant web-based information.

The search for Chinese academic papers began with a query of the CSET Merged Corpus of scholarly literature, including Clarivate’s Web of Science, Microsoft Academic Graph, China National Knowledge Infrastructure, arXiv and Papers With Code, using the terms "脑机接口 / brain-computer interface" for the years 2020-2022.[15] Some 1,562 China-affiliated papers[16] in English and Chinese were retrieved and reviewed as candidates for a basic corpus.

Underlying the selection task was the matter of scoping the target itself. “BCI research aimed at cognitive augmentation” or “cognitive enhancement beyond natural ability,”[17] while clear enough conceptually,[18] belie the fact that technology leading to this “human-plus” state has its origins in therapeutic uses—applications meant to reverse pathology. Removing medical uses entirely from the search, accordingly, suppresses the knowledge needed to project future states.[19]

Also, this paper intentionally avoids military applications, which are beyond its scope, as the topic is scrutinized by specialists and military uses can be inferred from *general improvements* in BCI’s function and design. [20] Defense needs, however, can be drivers for BCI breakthroughs, so some attention (e.g., drone control) had to be paid to this area as well.

Given these considerations, the decision was made to judge a paper’s *relevance* by relying on guidelines internalized by this study’s subject matter experts, namely, “whether a paper shows current or potential use of BCI for cognitive enhancement beyond restoring lost functionality.” To add rigor, the study’s two subject-matter experts (SMEs) were asked to make these judgments independently. Papers on which both SMEs agreed (106 of the original 1,562 titles) and another 35 papers gathered independently were chosen as a baseline for finding additional papers using the co-author relationships this first batch provided.[21] Some 473 more papers were identified, reduced to 370 after SME review, bringing the count to 511 papers.[22]

The surviving corpus of 370 “new” papers was expanded by leveraging their metadata and bibliographies. Some 47 of these papers that one or both SMEs rated “high” in relevance were used to generate additional papers by searching for co-authors *and cited references*. Another 214 from the second run rated by *both* SMEs as “on topic” (but not “high”) were also examined for new (co)author publications. Some 109 papers judged by one SME only as relevant were retained but not further exploited. This third-phase process yielded 244 more papers, reduced to 173 after review, for a sub-total of 684 vetted studies.

A fourth and final run examined the 30 most prominent Chinese authors in the expanded corpus for Chinese language studies missed in prior searches, yielding 25 more papers for a total of 709. The corpus was returned to the SMEs for a global reexamination of their relevance using insights gleaned from each vetting process, which eliminated 46 papers, and for characterization of their content. The final count stood at 663 on-topic studies.

Besides China-affiliated academic papers, the present study examined BCI-related patents assigned to China.[23] A search was conducted on the CSET unified patents dataset using the same BCI bilingual keywords used in the scholarly literature search.[24] Query fields included patent title, abstract and description in both English and Chinese. We considered a "China patent" to be a patent with at least one assignee or one inventor claiming a China affiliation.

Some 346 patent records were obtained and subjected to review for topic relevance. The 114 surviving records were returned to the SMEs for characterization by the same criteria used for the academic papers. The result was a body of 777 records of persons and organizations doing research judged to be consistent with the goal of BCI-augmented cognition. These data inform the following sections on scientists, organizations, and this study's analytic observations.

China's BCI Institutions

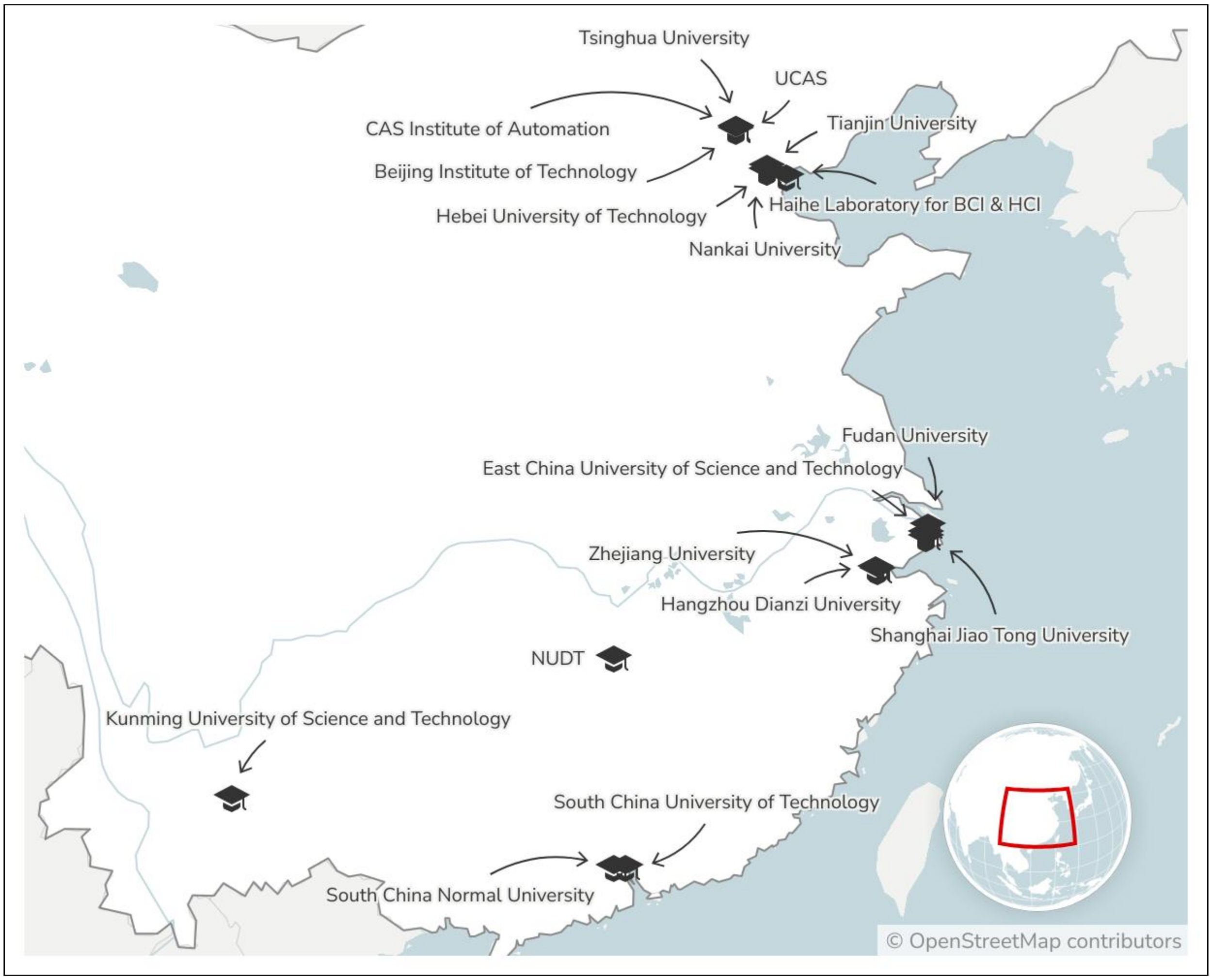
There were 280 unique institutional affiliations claimed by the first authors of 663 BCI papers, reduced to 129 affiliations by grouping subordinate units under their parent organizations.[25] The 15 most prominent are given in Table A:

Table A. First-Author Affiliations of Selected Chinese BCI Academic Papers

Affiliated Institution	Academic Papers
Tianjin University	95
Shanghai Jiao Tong University	55
Tsinghua University	52
University of Chinese Academy of Sciences (UCAS)	33
Fudan University	29
South China Normal University	29
Hangzhou Dianzi University	27
Kunming University of Science and Technology	26
Beijing Institute of Technology	25
National University of Defense Technology (NUDT)	24
Hebei University of Technology	23
South China University of Technology	22
CAS Institute of Automation	19
Zhejiang University	18
East China University of Science and Technology	14

Here are the same 15 institutions plus two others geolocated to show their distribution.[26]

Figure 1: China's top BCI research institutions (by paper count)



Source: Table A above.

Patents were assigned to 26 unique institutions, eight of which had three or more patents as follows:

Table B. Top China BCI Patenting Institutions

Institute	Patents
South China University of Technology	26
Chinese Academy of Sciences	17
Tsinghua University	15
Huazhong University of Science and Technology	10
Zhejiang University	7
Tianjin University	6
Shanghai Jiao Tong University	4
Shandong University	3

The small number of patents (114) relative to academic papers (663) precludes direct statistical comparison. Notably there were *no outliers*—patent assignees were present in the full corpus of BCI papers without exception. Some additional observations:

- "Chinese Academy of Sciences (CAS)" patent assignees are indeterminable from the data. A dozen second-tier units within CAS are cited in the academic studies, the most prominent being its Institute of Automation (自动化所). The CAS University, another high-scorer in the papers tally, may also figure into the balance.

- Wuhan's Huazhong University of Science and Technology (10 patents) scored modestly (6 papers) in the survey of first-author affiliations. That number rises to 18 papers in the full corpus, only one of whose authors claims a second affiliation. This is unusual, as most authors register multiple affiliations beyond their primary one. The other prominent BCI facility whose authors cite no secondary affiliations is Changsha's National University of Defense Technology.

- South China University of Technology's strong patents showing, absolutely and relative to its papers (12th of 15 institutions), is explained by its association with Guangdong's Pazhou Lab (琶洲实验室), which appears 43 times in the full studies corpus, split between researchers at South China University of Technology and South China Normal University.[27]

The following organizations, listed with a few of their highlights, are among the top performing Chinese BCI institutes based on published papers and noteworthy research.

- CAS Institute of Automation (中科院自动化所) besides its AI portfolio, also does BCI research. The institute's work on coding and decoding visual neural information is key to China's BCI development. A 2021 report, "BAAI AI Frontiers," listed among CASIA's achievements a robotic system that can "accurately implant flexible electrodes into the cerebral cortex of animals," facilitating China's broader use of invasive BCIs.[28]

- Fudan University's (复旦大学) Institute of Brain-inspired Circuits and Systems (类脑芯片与片上智能系统研究院) in 2021 announced China's first wireless BCI circuit for sending information between a chip and nerve cells. Team leader Ye Dawei (叶大蔚)[29] claims it "outperforms foreign versions on many levels" at half the cost.[30] The device is currently installed on the skulls of freely moving mice.

- Haihe Laboratory for Brain-Computer Interaction and Human-Computer Integration (脑机交互与人机共融海河实验室) was established in March 2023 under Tianjin University's leadership. The lab is a focal point for a consortium of national institutions and some 60 top scientists led by academician Gu Xiaosong (顾晓松) from the university's School of Medicine.[31] It aims to solve technical problems delaying BCI's wider adoption.[32]

- Hangzhou Dianzi University (杭州电子大学) hosts both a "Key Laboratory of Brain-Machine Collaborative Intelligence (脑机协同智能重点实验室) and an International Joint Research Center for Brain-Machine Collaborative Intelligence

(脑机协同智能技术国际联合研究中心). The latter is sponsored by the Ministry of Science and Technology and is joined by "renowned experts" from Germany, Italy, Japan, Russia, and the United States.[33]

- Nankai University's (南开大学) College of Artificial Intelligence, another Tianjin facility, while not a high-scorer in the tally (five papers totally), merits inclusion here based on its early development of "interventional" BCI—a minimally invasive technique that puts electrodes in contact with motor cortex by entering the cranium through the jugular vein. Duan Feng (段峰) led the research with support from the People's Liberation Army (PLA) 301 Hospital.[34]

- Shanghai Jiao Tong University's (上海交通大学) Ruijin Hospital BCI and Neuromodulation Center (瑞金医院脑机接口及神经调控中心) was founded in 2020 with the goal of using BCI to address depression and other neuropsychological illnesses, (i.e., BCI's "affective" applications.)[35] It aims to "implant chips into patients' brains via a minimally invasive surgery" followed by electrical stimulation based on AI analysis.[36]

- South China University of Technology's (华南理工大学) Center for BCI and Brain Information Processing (脑机接口与脑信息处理中心) was established in 2007. It hosts multiple BCI "platforms" (平台) with a wide range of equipment, supported by alliances with hospitals and "overseas institutions." The center is partnering with the Chinese IT company iFlytek on BCI development.[37]

- Tianjin University (天津大学) is at the forefront of China's BCI development. In 2019, the university unveiled its "Brain Talker" (脑语者) processing chip, which is able to separate signals from noise efficiently. The chip will "replace traditional computer devices used in BCI."[38] A faster chip is under development.[39] The university was using a 100-target "very large instruction set" matrix in 2019 and a matrix with 200+ squares in 2023.[40]

- Tsinghua University's (清华大学) BCI Lab (脑机接口研究组), established in 2004, studies the application of BCI to cognitive skill assessment for use in "human-machine collaboration."[41] Tsinghua is pushing the frontier on high-throughput, EEG-based interfaces. It was the first in China to implement non-invasive BCI technology based on steady-state visually-evoked potential (SSVEP).[42]

- Zhejiang University (浙江大学) was first in China to do invasive BCI research and was implanting electrodes in primates by 2012.[43] Its Double Brain Center (双脑中心)[44] dates from 2018; its School of Brain Science and Brain Medicine (脑科学与脑医学学院) set up in 2019 hosts a National Key Laboratory of Brain-computer Intelligence (脑机智能全国重点实验室).[45] By 2021, the university's BCI and Intelligence Integration Team were building hybrid invasive/non-invasive BCI systems.[46]

Finally, it is worth noting that eight of 10 BCI organizations singled out in an earlier CSET study on Chinese AGI precursor research based on "internet sources judged to be reliable" are replicated in this SME-vetted inventory.[47]

China's BCI Scientists

Some 1,901 non-unique China-affiliated author names were captured from the 663 BCI papers, by the following rules: include up to three China-based authors per paper,[48] including first author, second author if work was shared equally, corresponding author (if specified), and/or the last author (typically the senior person).[49] Removing duplicates left 993 unique authors. Here are the most prominent (author's name appears on the bylines of eight or more papers):

Table C. Most Frequent (Co)Authors of Selected China BCI Studies

Authors	Papers	Institutions
MING Dong (明东)	62	Tianjin University, Tianjin
LU Baoliang[50] (吕宝粮)	40	Shanghai Jiao Tong University, Shanghai
XU Minpeng (许敏鹏)	34	Tianjin University, Tianjin
GAO Xiaorong (高小榕)	33	Tsinghua University, Beijing
PAN Jiahui (潘家辉)	28	South China Normal University, Guangzhou
KANG Xiaoyang (康晓洋)	24	Fudan University, Shanghai
FU Yunfa (伏云发)	17	Kunming University of Science and Technology, Kunming
HE Huiguang (何晖光)	17	CAS Institute of Automation, Beijing
JUNG Tzyy-Ping (钟子平)	17	Tianjin University, Tianjin[51]
LI Yuanqing (李远清)	17	South China University of Technology, Guangzhou
CHEN Xiaogang (陈小刚)	14	CAMS and Peking Union Medical College, Beijing
LIU Jingquan (刘景全)	14	Shanghai Jiao Tong University, Shanghai

CHEN Xun (陈勋)	13	University of Science and Technology of China, Hefei
JIN Jing (金晶)	13	East China Univ. of Science and Technology, Shanghai
KONG Wanzeng (孔万增)	12	Hangzhou Dianzi University, Hangzhou
LI Xiaojian (李骁健)	12	Shenzhen Institute of Advanced Technology, Shenzhen
QIU Shuang (邱爽)	12	CAS Institute of Automation, Beijing
HU Dewen (胡德文)	10	National University of Defense Technology, Changsha
WANG Yiwen (王怡雯)	10	Hong Kong University of Science and Technology, HK
CAI Xinxia (蔡新霞)	9	State Key Lab of Transducer Technology, CAS, Beijing
JI Bowen (吉博文)	9	Shanghai Jiao Tong University, Shanghai
WANG Xingyu (王行愚)	9	East China Univ. of Science and Technology, Shanghai
WU Dongrui (伍冬睿)	9	Huazhong University of Science and Technology, Wuhan
ZHOU Zongtan (周宗潭)	9	National University of Defense Technology, Changsha
PENG Yong (彭勇)	8	Hangzhou Dianzi University, Hangzhou

These data comport well with information on recipients of the 2023 Huanao Award (华瑙奖) for BCI research. The award is jointly conferred by the Haihe Laboratory for Brain-Computer Interaction and Human-Computer Integration (see above) and Tianjin's National Key Laboratory of Advanced Medical Materials and Devices (先进医用材料与医疗器械全国重点实验室).[52]

Table D. Huanao Scholar Award Recipients and Prominent BCI Paper Authors

Huanao Scholar Awardees	CSET-Selected papers
Lifetime Achievement Award	
GAO Shangkai (高上凯)	1
WANG Mingshi (王明时)	0
Outstanding Scholar Award	
GAO Xiaorong (高小榕)	33
HU Dewen (胡德文)	10
LI Yuanqing (李远清)	17
YAO Dezhong (尧德中)	3
ZHAO Guoguang (赵国光)	0
Distinguished Young Scholar Award	
CHEN Xun (陈勋)	13
CHENG Longlong (程龙龙)	0
JIN Jing (金晶)	13
LI Xiaojian (李骁健)	12
WANG Yijun (王毅军)	7
WANG Yiwen (王怡雯)	10
WU Dongrui (伍冬睿)	9
WU Xia (邬霞)	4
XU Minpeng (许敏鹏)	34
YIN Erwei (印二威)	4

That is, 13 of the 15 working BCI scientists recognized with a Huanao Award authored papers selected as significant by two U.S. neuroscientists using independent criteria. One outlier, Zhao Guoguang, was awarded for "clinical applications" of BCIs, which is outside the present study's scope.[53] The other, Cheng Longlong, achieved prominence for building a "brain talker chip" (see above), worn externally and designed to replace traditional computer devices.[54] Both Zhao and Cheng appear as authors in the collected corpus but not in positions of prominence.

Authorship distribution for these papers reflects a familiar pattern, wherein scientists leading the execution of the research claim first- and second-author status, while those guiding the research appear toward the end of the byline. The 663 papers studied had 501 unique first authors, 10 of whom had five or more papers in 2020-2023.[55] By contrast, there were 238 unique "final" authors, fewer than half the number of unique first authors, 20 of whom made six or more appearances.[56] Pan Jiahui (潘家辉) excepted, all the most prominent authors in this study fall into one group *or* the other, that is, hands-on researchers presumably doing novel science versus more senior persons making administrative decisions.

There is value in capturing details on both types, top first authors and those who register highest overall. The following scientists are drawn proportionately from the two groups:[57]

Prominent Chinese BCI Scientists

CHEN Xiaogang (陈小刚) is an associate researcher at the Chinese Academy of Medical Sciences and Peking Union Medical College (中国医学科学院北京协和医学院) in Tianjin. His PhD is from Tsinghua in biomedical engineering and his research areas are neuromodulation, BCI and intelligent robots, with publications in multiple sub-disciplines. He belongs to several industry associations, has won global robotics competitions, and has three personal patents.[58]

CHEN Xun (陈勋) earned a PhD from the University of British Columbia in 2014 and is a full professor at Hefei's University of Science and Technology of China, where his work on BCIs, signal processing and image analysis won him high awards and entry to national-level "key" projects.[59] He is also director of a "Joint Laboratory for Brain and AI" (脑机智能实验室) with Zepp Health Corporation (华米科技)[60] engaging in invasive and non-invasive BCI development.[61]

GAO Xiaorong (高小榕) received a doctorate from Tsinghua's Biomedical Engineering Department in 1992 and continues there as a professor today. Gao is recognized worldwide and credited with founding BCI research in China, in particular SSVEP technology.[62] His long-term research focuses on practical and theoretical analysis of EEG data for clinical applications and as a path toward understanding brain function. His publications number over 100, many highly cited.[63]

HU Dewen (胡德文) earned an MS degree from Xi'an Jiaotong University in 1986, joined the People's Liberation Army in June of that year, and was a visiting scholar at the UK's University of Sheffield in 1995-1996. Hu's PhD is from the National University of Defense Technology (1999),[64] where he researches brain, cognitive science, and control science. He received multiple Chinese "talent" awards and is author of more than 300 papers.[65]

JIN Jing (金晶) received a PhD from Shanghai's East China University of S&T in 2010, where he serves as professor and chair of its Automation Department.[66] Jin is one of China's most widely connected BCI researchers, serving on the boards of numerous top-ranked BCI journals and in industry organizations. His research focuses on human-machine hybrid intelligence, signal processing and the development of exoskeleton robots.[67]

KANG Xiaoyang (康晓洋) earned a doctorate from Shanghai Jiao Tong University in 2016, then did postdoc research at the Laboratory for Soft Bioelectronic Interfaces, École Polytechnique Fédérale de Lausanne. In 2018 he joined Fudan University's faculty where he studies biomedical microelectronic devices, neural engineering, and brain-computer interaction. Kang's research on soft implantable neural interfaces has been funded by municipal and state-level bodies.[68]

LI Xiaojian (李骁健) received a PhD from CAS's Institute of Biophysics in 2010, did postdoc work at the Medical College of Georgia at Augusta University under Joe Tsien

(钱卓) in 2010-2013,[69] and was a research associate at Illinois' Northwestern University until taking his present post at CAS's Shenzhen Institute of Advanced Technology in 2018.[70] Li founded We-Linking Medical (see below), where he develops optically controlled interfaces.[71]

LI Yuanqing (李远清) earned a PhD from South China University of Technology in 1997 and stayed on as faculty, with stints at Japan's RIKEN Brain Science Institute (2002-2004) and Singapore's Information and Communication Institute (2004-2008), where he researched brain signal analysis. His Center for BCI and Brain Information Processing (脑机接口与脑信息处理中心) collaborates with iFlytek on "brain-computer collaborative hybrid intelligence."[72]

LU Baoliang (吕宝粮) is a professor at Shanghai Jiao Tong University, director of its Center for Brain-like Computing and Machine Intelligence (仿脑计算与机器智能研究中心) and head of the affiliated Center for Brain-Machine Interface and Neuromodulation (脑机接口及神经调控中心) and Ruijin-MiHoYo Lab. He earned a PhD at Kyoto University in 1994, remaining in Japan until 2002 at RIKEN in Nagoya. Lu specializes in affective BCI and emotion recognition.[73]

MING Dong (明东), a Tianjin University PhD (2004), is now vice president of the university, professor in its School of Precision Instrument and Optoelectronics Engineering and head of the Tianjin Brain Science and Brain-inspired Research Center (脑科学与类脑研究中心). Ming holds the record for number of papers selected for this study as does the university itself. His research interests range from neural stimulation and interfaces to neural sensing and imaging.[74]

PAN Jiahui (潘家辉) earned a PhD at South China University of Technology in 2014 under Li Yuanqing in pattern recognition and intelligent systems.[75] He is now vice dean of South China Normal University's School of Software and director of the affiliated Brain-Computer Interaction and Hybrid Intelligence Research Center (脑机交互与混合智能研究中心), founded in 2019.[76] Pan's research is on BCIs, brain signal processing and pattern recognition.[77]

PENG Yong (彭勇) is a professor at Hangzhou Dianzi University and deputy director of its Institute of Cognitive and Intelligent Computing (认知与智能计算研究所).[78] He was awarded a PhD from Shanghai Jiao Tong University in 2015 after two years studying in the University of Michigan's Department of Electrical Engineering and Computer Science. Peng researches machine learning, pattern recognition, and EEG-based BCI.[79]

WANG Yiwen (王怡雯) did pre-doctoral work at Hefei's University of Science and Technology of China. In 2008 she earned a PhD from the University of Florida under Professor Jose C. Principe,[80] and was with Zhejiang University before joining the Hong Kong University of Science and Technology's faculty in 2017. Wang's work in computational neuroscience and neural decoding for BCI has won her top spots on IEEE committees and on the boards of leading IEEE journals.[81]

WU Dongrui (伍冬睿) received a PhD in electrical engineering from USC, Los Angeles in 2009 and is now a professor with Huazhong University of Science and Technology in Wuhan researching BCI, affective computing and computational intelligence.[82] Wu's BCI and Machine Learning Laboratory (脑机接口与机器学习实验室) within the university's School of Artificial Intelligence and Automation is funded by state and local governments and by Huawei, Alibaba, Baidu, and Ant Group.[83]

XU Minpeng (许敏鹏) earned a PhD from Tianjin University in 2015 and is now vice dean of its Academy of Medical Engineering and Translational Medicine, where he researches BCI. Xu holds positions of importance in numerous industry associations and has received significant national-level funding since 2017. He was at UC San Diego's Institute for Neural Computation from 2014 to 2015.[84] In 2022, Xu directed China's first open-source BCI platform "MetaBCI."[85]

China's BCI Companies

According to a Chinese ministry report, in 2023 there were more than 100 BCI companies in China, up from around half that number two years prior.[86] A survey of the Chinese BCI industry in the technology news journal *36Kr* noted that "outside of the medical scene, BCI companies have their sights on the brain science research market, mainly domestic brain science and brain-like research, neuroscience, language and cognitive function, psychology research and other laboratories, and on providing scientific research tools and services."[87]

The following ten Chinese BCI companies and one industry association surfaced while doing Internet searches on scientists and institutions for this study, or as the secondary affiliations of authors who contributed to the corpus of papers. Within this sample are companies whose business models address both the therapeutic and cognitive facilitation aspects of BCI.

Neuracle (博睿康)

Neuracle was established in 2011 by a team from Tsinghua University's Neural Engineering Laboratory (神经工程实验室) and continues to benefit from the association. The company specializes in the research, development, and production of non-invasive and minimally invasive (微创脑机接口) BCIs. Its main customers include several of the universities highlighted above.[88] The company's wireless EEG acquisition system and transcranial electrical stimulation products are used in biomedicine, psychology, cognitive science, neuroscience, and neuromodulation.[89]

NeuraMatrix (宁矩科技)

NeuraMatrix is another company incubated by Tsinghua University. Stood up in 2019, it builds active implantable systems interfacing with the human body and artificial devices. Whereas China has decades of experience with non-invasive BCI systems, NeuraMatrix was China's first company to build an implantable device. Unlike other Chinese BCI projects whose goal is to alleviate disability, NeuraMatrix openly states its aim to augment the cognitive power of people in general "by effectively merging human and artificial intelligence." Its products include electrode materials, a neural interface chip, and "infinite multi-point interface equipment." [90]

Zhiran Medical (智冉医疗)

Zhiran was founded in Beijing in 2022, with composite experience dating back a decade. The company offers "precise diagnosis and treatment of neurological diseases."[91] It was created by Fang Ying (方英)—a researcher at China's National Center for Nanoscience and Technology (国家纳米科学中心) and former Harvard student[92]—and by current CEO Song Qi (宋麒), a University of Iowa PhD recipient, who worked at GE's Global R&D Center in New York.[93] Their team researches neural tassel electrodes (神经流苏电极) and ultra-flexible micro-electrode arrays.[94]

Xinzhida Neurotechnology (芯智达神经技术)

Also located in Beijing, Xinzhida Neurotechnology was founded in March 2023 under Luo Minmin's (罗敏敏). management. Luo is co-director of the Chinese Institute for Brain Research (北京脑科学与类脑研究中心), which studies brain-inspired AI and BCI.[95] The firm appears to be a brokerage operation, whose main business is "technology transfer, promotion and exchange." [96] Xinzhida leads the Intelligent Brain-Computer System Enhancement Program (智能脑机系统增强计划) stood up in April 2023 to integrate Beijing area BCI resources and "build the world's leading brain-computer interface equipment."[97]

Stairmed (阶梯医疗)

Founded in August 2021 in Shanghai, Stairmed builds implantable BCIs aimed at human body function restoration and function enhancement (机能增强). The company produces "ultra-flexible micro-nano electrodes (超柔性微纳电极) yielding a "spatial sampling density" of 1024 channels/cubic mm.[98] Stairmed was founded by Zhao Zhengtuo (赵郑拓), a researcher at CAS's Center for Excellence in Brain Science and Intelligence Technology (脑科学与智能技术卓越创新中心) and by Li Xue (李雪), also at CEBSIT and head of its Multimodal Neural Interface Research Group. Zhao's PhD is from the University of Texas at Austin. Li earned his PhD at Rice University.[99]

Tianqiao and Chrissy Chen Institute (陈天桥雒芊芊研究院)

Founded at Caltech in 2016 by online gaming pioneer Chen Tianqiao (陈天桥) and his spouse Chrissy Luo (雒芊芊), the institute established in 2020 and 2021 two "Frontier Labs" (前沿实验室) for brain research, one at Huashan Hospital (华山医院) in Shanghai headed by neuroscientist Gerwin Schalk,[100] the other at the Shanghai Mental Health Center (上海精神卫生中心), whose vision statement reads: "To enrich people's lives with brain- and mind-related technology." The institute intends to extend the development of its invasive BCI products beyond therapeutics to cognitive augmentation.[101]

NeuroXess (脑虎科技)

NeuroXess, also in Shanghai, produces invasive BCI products[102] aimed at "twinning" (孪生) human and artificial intelligence.[103] Its "flexible BCI system" benchmarks the U.S. company Neuralink's products and was inspired by work that its founder Tao Hu (陶虎) did at Tufts University.[104] Tao, who is also at CAS's Shanghai Institute of Microsystem and Information Technology (上海微系统与信息技术研究所), aims at cognitive augmentation and a merger with AI. Along the way, BCI will support "emotional regulation and cognitive assessment."[105] Tao predicts the "digitization of humans" through BCI.[106]

Neuracom (衷华脑机)

Neuracom was founded by Huang Li (黄立) in 2021. The company offers "a one-stop implantable brain-computer interface system" claimed to be on a par with the world's best.[107] Neuracom is part of Wuhan's China Optics Valley Brain Science Industrial Base (中国光谷脑科学产业基地) in the city's East Lake High-tech Development Zone (东湖高新区), which is host to Huazhong University of Science and Technology's Brain Institute, CAS's Institute of Automation, and other leading organizations, whose collective goal is to build "the first brain-computer interaction industrialization project in Central China."[108]

BrainCo (强脑科技)

BrainCo, with branches in Hangzhou, Shenzhen, and Boston, was founded in 2015 by Han Bicheng (韩璧丞) and a team of fellow Chinese students at the Harvard Innovation Lab. Besides Harvard, BrainCo's website lists MIT, Yale University, Boston University, and other foreign entities as collaborators.[109] Its products, based on non-invasive technology, include a bionic hand, an "intelligent" prosthetic leg, neurofeedback sleep aids and an attention-monitoring headband that debuted in a Zhejiang elementary school. BrainCo claims to have funding in excess of USD 200 million and U.S. FDA approval for its products.[110]

We-Linking (微灵医疗)

We-Linking was established in April 2019 in Shenzhen with branches in Beijing, Suzhou, and Maryland and is credited as being a "full-suite" producer of invasive BCI products.[111] Its founder, Li Xiaojian (李骁健) is affiliated with CAS's Shenzhen Institutes of Advanced Technology (深圳先进技术研究院) and, like many of the entrepreneurs listed here, trained and worked extensively in the United States.[112] In November 2023, the company and its CAS affiliate established a Brain-Computer Intelligent Integration Technology Joint Laboratory (脑机智能融合技术联合实验室) for implantable BCI.[113]

Brain-Computer Interface Industry Alliance (脑机接口产业联盟)

This BCI industrial alliance—China's first—was formed in February 2023 under Ministry of Industry and Information Technology auspices with support from Tsinghua and other major institutions.[114] It is led by Yu Xiaohui (余晓晖), head of the China Academy of Information and Communications Technology (中国信息通信研究院).[115] Its secretary-general Li Wenyu (李文宇) stated in May 2023 that Chinese researchers have experimented on humans and other primates using implantable and interventional (介入式) technology.[116] As of November 2023, some 151 BCI-related organizations had joined.[117]

Content Analysis

Besides collecting metadata on China's BCI infrastructure, the present study also analyzed the *content* of papers and patents to assess the research itself.

Based on an initial review of a subset of the literature, this study's two subject-matter experts built a taxonomy that was used to classify each paper/patent. One focus of the taxonomy was experimental technique. Primary distinctions were "recording" for brain signal read-out or "stimulation" for signal input, and whether the data were obtained using invasive means ("brain implant") or not. Given the preponderance of approaches using EEG, "EEG" was used as a separate category for studies using EEG. Since EEG always involves recording, no separate "recording" label was used for these studies.

Recording and stimulation techniques that used methods other than EEG or brain implants, such as fNIRS (functional near-infrared spectroscopy),[118] fMRI (functional magnetic resonance imaging),[119] or ultrasound, but also studies supplementing neural signals with non-neural signals (such as eye movements), were labeled as "other." Studies that did not focus on a specific application, but rather on the data science of extracting predictive features from neural signals for a variety of applications were labeled "algorithm development."

A second focus of the taxonomy was on the application area. We used "hardware engineering" for papers/patents on developing new hardware, such as novel material science, new micro-electrodes, and experimental platforms. "Autonomous robot control" included driving-related applications such as detecting braking signals, as well as wheelchair and exoskeleton control, along with control of small robots or unmanned aerial vehicles (UAVs).

"Emotion detection" labeled papers/patents on extracting information about users' emotional states. "Cognitive state monitoring" was used as a label for studies/patents that focused on extracting information about non-emotional cognitive states such as focused attention, cognitive load, or error processing. The latter category also included a few studies on epilepsy monitoring.

“Communication” included papers/patents focused on allowing the user to communicate without voluntary muscle movement. This included applications to decode inner (i.e., imagined) speech and applications such as P300 spellers[120] and studies using SSVEP (steady state visually evoked potential)[121] to allow users to select particular items from streams of information. It also included motor imagery or the ideation of moving muscles, if the focus was on using the signals to allow users to communicate.

“Fatigue detection” included studying signals indicating users’ fatigue or vigilance. Studies on the ethical aspects of using BCI were labeled “ethics.” Lastly, we used “review/editorial” to label studies that reviewed the field but did not provide primary data.

Figures 2 and 3 depict, respectively, the numbers of papers and patents associated with these 14 categories.

Figure 2. Chinese BCI Studies—Topical Characterization

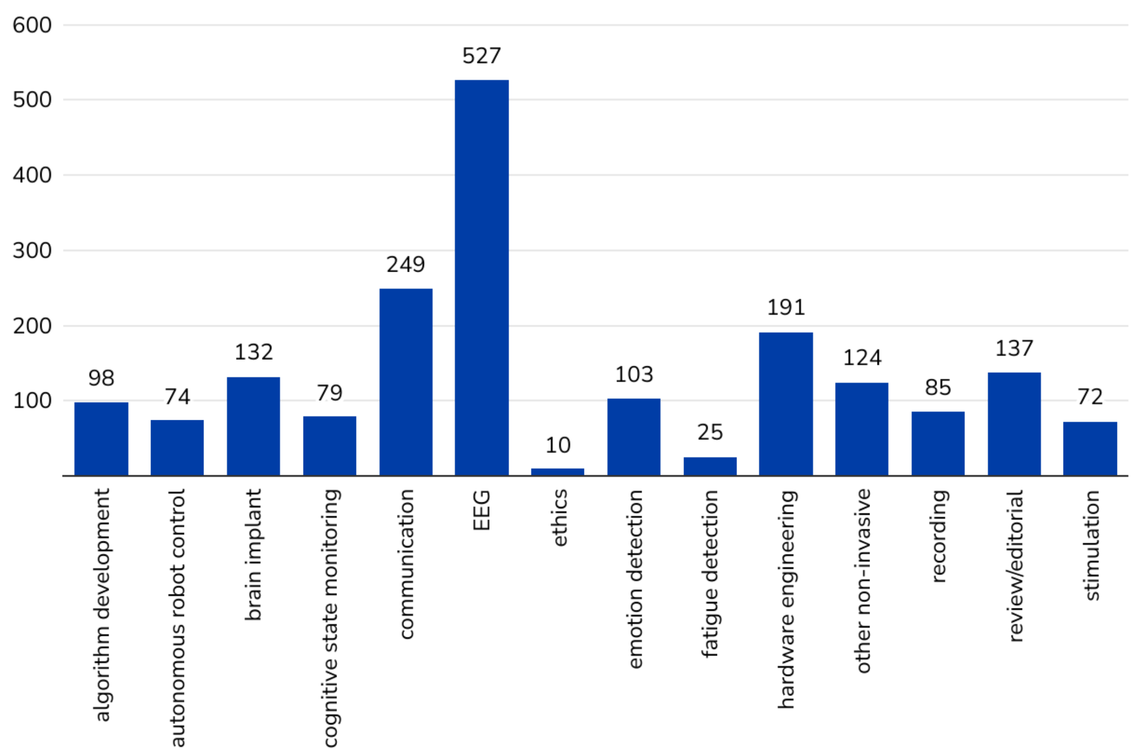
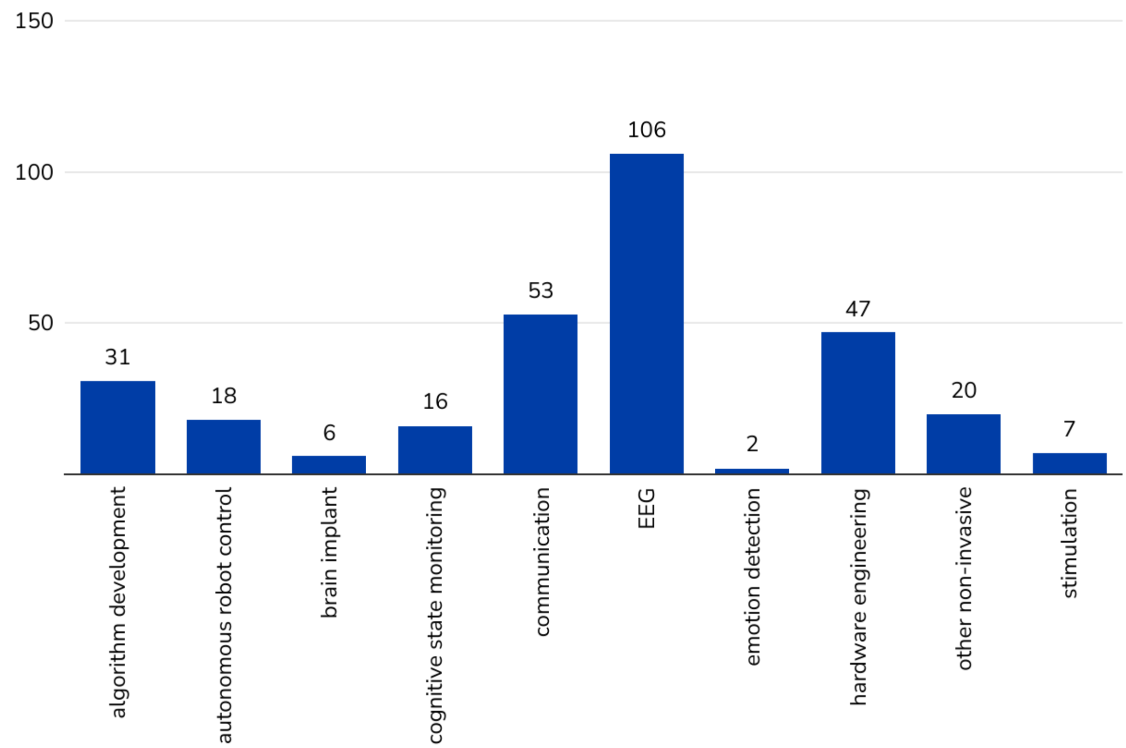


Figure 3. Chinese BCI Patents—Topical Characterization



Not surprisingly, given the relative simplicity of collecting brain data using EEG, there was a preponderance of studies using that technique. In comparison, since most invasive BCI require a skilled neurosurgeon and have complex ethical implications, there were many fewer papers using brain implants.

The large number of studies with a "communication" label was due to many studies using EEG for P300/SSVEP-type applications. The relatively large number of studies focusing on emotion detection was remarkable, in particular relative to the general BCI literature (i.e., not just limited to that including Chinese authors).

The large number of papers on improving decoding of EEG signals is striking. This confirms the known issue of interpretability of EEG signals, poor signal quality, and the determination of the labs to overcome these challenges with state-of-the-art machine learning techniques.

Expert Assessments

The following evaluations of China's BCI capabilities are provided by this study's two subject-matter experts, Drs. Wang and Riesenhuber, based on materials they examined here and their knowledge of global trends.

Dr. Jennifer Wang, neurotech SME for R&D programs

China's BCI community has focused on EEG—a non-invasive interface to advance brain read-out technology that is low-cost, low-risk, as well as easy to operate and scale. However, recording signals from outside the brain is like listening to a concert through walls; interpreting scalp electrical signals has historically been challenging due to its diffuse and noisy nature. The desire to overcome this challenge is reflected in the large volume of data science studies reported here that leverage state-of-the-art machine learning techniques to improve feature analysis of brain signals, which can be used for controlling devices or revealing mental states. The massive effort to improve EEG signal analysis is remarkable and may have resulted in successes such as a "world-first" claim by Xinhua in May 2023, where a Nankai University laboratory demonstrated robotic arm control through an EEG BCI interface in a macaque monkey.[122] In this invasive (interventional) study, the electrodes are implanted inside a brain blood vessel for recording. Many obstacles remain for invasive BCI devices to be safe for humans.

The analysis of publications presented here suggests that in addition to clinical rehabilitation, there's a strong push towards understanding brain read-out for a multitude of practical uses in the general population. These applications are mainly targeted at improving life quality and providing next-level biofeedback. Applications for autonomous driving include driver intent-triggered assistive braking and driver fatigue detection; using brain signals to control wheelchairs, computer games or smart home functions. Being a leading manufacturer of uncrewed autonomous vehicles (UAVs), China also seeks to find more sophisticated UAV/swarm control algorithms using BCIs to surpass existing computer algorithms. Developing brain-controlled Chinese character input has a notable number of studies in our review. This offers patients with motor deficits a way of communication and an additional method for healthy people to interact with their electronic devices. The input rate (characters per minute) remains low for practical use in the general population.

Optimizing learning and deriving higher intelligence is another theme observed in recent publications. EEG-based BCI monitors have been tested in Chinese schools as trial biofeedback devices designed to measure concentration before being halted after media backlash. Emotional detection algorithms may have similar uses for monitoring mood and building emotionally-informed digital assistants/companions to increase work productivity and provide emotional comfort for an aging population. Several studies tested if brain data from multiple people performing the same task, or a mixture of human and machine intelligence, could more efficiently solve complex problems.

Overall, the literature review reflected China's investment in using non-invasive BCIs to develop ready-to-use devices to facilitate direct interaction of user intent (brain signals) with the world. For this emerging field, we found nine ethical editorial articles discussing issues associated with BCI use, including user privacy and informed consent.

Dr. Max Riesenhuber, Georgetown University, Department of Neuroscience

When surveying the literature on BCI, it is helpful to distinguish between "non-invasive" and "invasive" approaches. The former are mostly based on scalp electroencephalography (EEG) or other techniques (such as functional near-infrared spectroscopy, fNIRS) that do not require surgical implantation of neural recording and/or stimulation equipment. These techniques, while usually providing a relatively coarse picture of neural activity, have the critical advantage of ease of application. In contrast, "invasive" devices are placed inside the cranium, providing much improved signal quality and the ability to record from and stimulate precisely defined neuronal targets, at the expense of requiring surgical implantation.

These differences give rise to different application profiles for invasive and non-invasive techniques. While conventional EEG BCI techniques (such as P300 or SSVEP) could only extract a few bits or maybe tens of bits per minute of information from the

EEG signal,[123] newer analysis techniques based on advanced machine learning have increased the information rate obtainable from EEG-based BCI by an order of magnitude or more.[124] There are a large number of papers by Chinese scientists describing related efforts to improve the amount of information that can be extracted from the brain using non-invasive techniques. These data rates are already sufficient for a major application area apparent from the literature survey, that of using BCI, in particular non-invasive BCI, to extract private information from healthy individuals' brains, such as cognitive states (attention, vigilance, fatigue, deception) or mood/emotional states. In those cases, BCI systems can provide information that would otherwise not be readily accessible.

Correspondingly, many of the more interesting applications of BCI in healthy individuals focus on cognitive state detection, such as monitoring of cognitive load, level of attention, vigilance, or fatigue—which can be important, for instance, for monitoring pilots or drivers. In addition, there were a surprisingly large number of papers on emotion processing, such as detecting the emotional states of participants (which could be as simple as positive/neutral/negative, or aiming for a more fine-grained classification). Part of the reason for the substantial number of studies on this area could be that emotion detection is a "sweet spot" for BCI in healthy individuals: information on the emotional/cognitive state of an individual is of interest for a variety of applications and can be read out using cheap and non-invasive EEG.

In contrast, the use of non-invasive BCI in healthy individuals to control vehicles such as UAVs (and even UAV "swarms") reported in the Chinese literature can be considered gimmicks at this point, as the data rates and system performances are much lower than what can be obtained via conventional manual control.[125]

As is evident from the Chinese literature, the capabilities of EEG-based BCI systems will likely improve in the near future due to refined algorithms (permitting higher performance, faster training, and/or inter-subject transfer) and electrode technology (for higher signal quality, easier setup and longer recording durations) and the inclusion of complementary, non-neural sources of information such as eye movements, galvanic skin responses, visual information (analyzed by conventional ML techniques, e.g., for emotion detection by facial expressions), or speech signals.

There will also likely be a wider range of applications for EEG-based BCI systems, driven by the simplicity of EEG acquisition and its low cost. The patent survey revealed patents in a range of novel areas, including piano training, meditation training, measuring personality traits and carsickness prevention, to name just a few (on a side note, several patents on adversarial attacks on EEG-based BCI systems stood out as well).

In contrast to the limits of non-invasive techniques, invasive techniques have the advantage of vastly increased bandwidth, in other words, the ability to extract orders of magnitude more information about the brain's neural activity than possible with surface-based techniques such as EEG or fNIRS, as well as much higher specificity, which is particularly important for neuro-stimulation applications. Considering these advantages, it is not surprising that a second major focus of the surveyed Chinese research appears to be on reducing the complexity and invasiveness of direct neural recordings.

For instance, in the U.S., novel "neuropixel" electrodes allow the simultaneous recording from more than a thousand channels.[126] The Chinese literature describes the development of similar systems. A large number of surveyed research papers describe the development by Chinese teams of flexible electrodes and thin-film devices that better conform to the (soft, moving) brain and allow longer and more consistent recordings, of new electrode materials, miniaturized high-capacity recording chips, wireless transmission circuits, automated implantation devices and novel, fully implanted systems, with recording as well as stimulation capability (the latter either via conventional electric stimulation or by optical means, to be used in optogenetic applications).

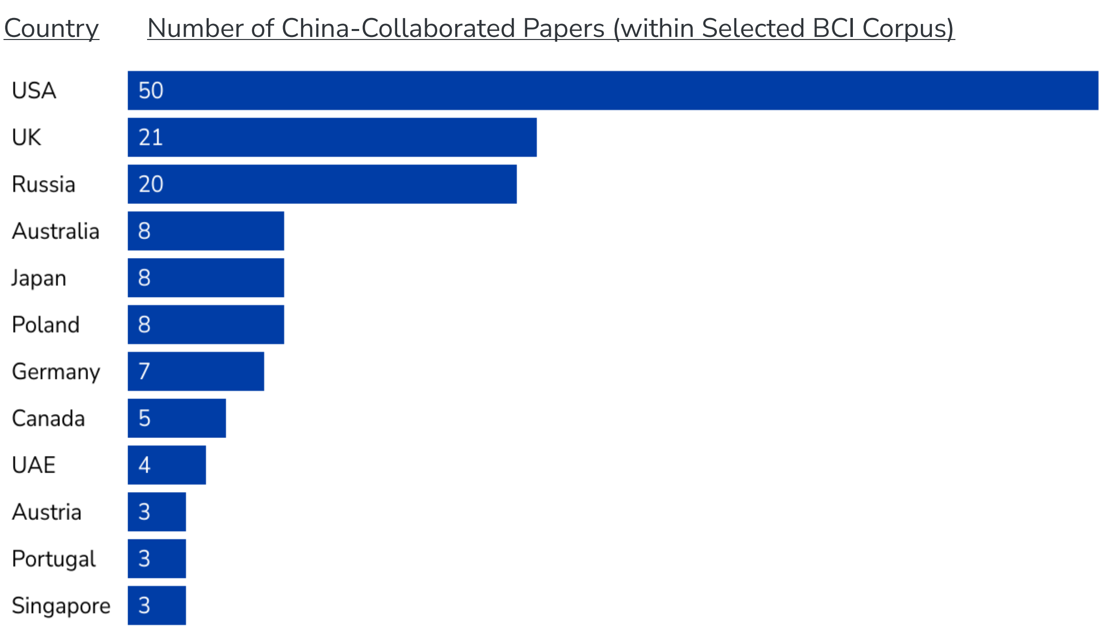
The comprehensiveness and multi-level approach of this Chinese research, encompassing all stages from electrode materials over implantation devices to signal transmission, make it highly likely that within the near future, there will be the capability for minimally-invasive high-bandwidth neural recording and stimulation, which will dramatically increase the potential of BCI applications, due to data rates that are either higher than obtainable via conventional means (such as manual responses) and/or the ability to read out and even modulate cognitive states (including emotional states).

Global Dependencies

We understand "global dependency" as the reliance of states on each other's knowledge or skills to develop and enhance their research. Each state has its own unique learning and teaching practices, supporting infrastructures, as well as ethics and laws that regulate research and affect its progress. Hence, political borders can confine research, and collaborating with foreign partners may help combat state-centric deficiencies.

While China has indigenous expertise in BCI, it is important to examine if and how China has gained from foreign collaborations. According to metadata in the 663 China-authored papers gathered for the present study, China's top collaborators in BCI research are U.S. and UK universities. China also worked with institutions in 19 other countries.[127] Figure 4 depicts the top 12 foreign collaborators with China on BCI-related publications. Not shown are collaborations with South Korea and Ethiopia (two publications each), and with Switzerland, Greece, Denmark, India, Finland, Slovenia, and Spain (one each).

Figure 4. China Collaborates Most Often with the United States for BCI Research (2020-2023)



U.S.-based scientists were the most frequent foreign collaborators with Chinese scientists, contributing to 50 BCI-related papers relevant to our search. These publications were affiliated with 21 different U.S.-based institutions and 32 China-based institutions. Notably, four of the 50 U.S. collaborations were with "Seven Sons" universities in China: two papers were affiliated with the Beijing Institute of Technology, one with the Nanjing University of Science and Technology, and one with the Northwestern Polytechnical University. The "Seven Sons of National Defense" (国防七子) are Chinese universities that train talent and work on technical projects of interest to the People's Liberation Army (PLA).[128] They are not administered directly by the PLA, and students tend to be civilians, but researchers at these universities do collaborate extensively with the PLA on basic and applied research.[129]

Northwestern Polytechnical University, for example, produces the most employees at China's largest defense company, the Aviation Industry Corporation of China, and has a scholarship program specifically for students looking to work there.[130] Beijing Institute of Technology is a top feeder for many defense companies in China and has a strong relationship with China North Industries Corporation (which is on the U.S. Department of Commerce's Bureau of Industry and Security Entity List), having signed strategic cooperation agreements with the company.[131]

Outside of the Seven Sons, other Chinese universities that collaborated with U.S. institutions had ties to China's defense industry. Shanghai Jiao Tong University has helped the PLA do cyber operations and openly operates joint research facilities with the PLA.[132] Zhejiang University and Huazhong University of Science and Technology are affiliated with Zhejiang Lab, which does AI research and has the NUDT on its oversight board.[133]

In all, some 21 U.S. institutions collaborated with Chinese organizations to publish BCI research. Here are the most prominent (number of papers):

Box 1: Major U.S. Institutions Collaborating with China on BCI

University of California San Diego (16)
University of Washington (6)
Lehigh University (4)
Massachusetts Institute of Technology (3)
Stanford University (3)

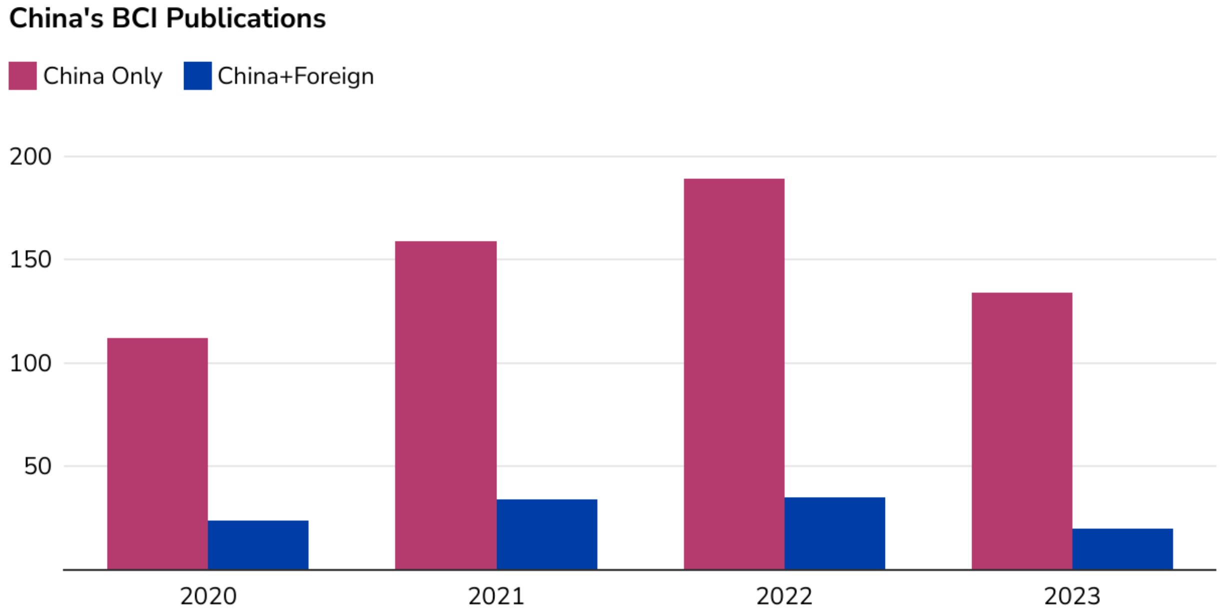
The following are the major Chinese BCI institutions collaborating with a U.S. institution:

Box 2: Major Chinese institutions collaborating with the U.S. on BCI

Tianjin University (14)
Shanghai Jiao Tong University (9)
Tsinghua University (5)
East China University of Science and Technology (4)
University of Electronic Science and Technology (4)
Fudan University (3)
Beijing Institute of Technology (3)

As indicated in Figure 4, there is a significant difference between the number of joint papers published by China's first and second most frequent collaborators. The United Kingdom had the second-most publications in collaboration with China-based institutions, with 21. The third most-frequent collaborator with China on relevant BCI research was Russia, with 20 publications, although this appears to be an anomaly.[134]

Figure 5. China-Only BCI Research Output vs. Foreign Collaborative Research Output



As Figure 5 shows, China published significantly more China-only research than collaborative research with foreign institutions between 2020 and 2023 in this topic area.[135] China's individual output on BCI was 110 in 2020, while the same year its co-authored foreign collaborations stood at 25 (around 19% of total research). This ratio declined slightly but steadily through subsequent years.

Overall, the majority of relevant BCI-related papers in China were published without foreign institutional collaborations: around 84% were published solely by Chinese institutions. These findings could imply that China's BCI research does not depend on direct collaborations with researchers outside China to be productive, and China's overt reliance on foreign partnerships in this area is decreasing.

Recommendations

Brain-computer interfaces began as therapeutic devices to treat pathology and will continue to fill that role into the future. We find these developments encouraging and strongly support the medical lines of BCI research—in China or anywhere. Alleviating human suffering is science at its best.

The same technology that can help restore neurological function, however, can enhance the cognitive capabilities of the general population across a range of applications that are only now being explored, which casts the enterprise in a more controversial light. The opportunities and risks of improved human-computer integration through BCI are apparent to China as well, as evidenced in the citations adduced in this study, in the papers we reviewed, and in Chinese sources that date back a decade or more.[136]

More recently, Chinese appreciation of the link between BCIs and cognitive enhancement was expressed at China's "First National Brain-computer Interface Conference" (全国首届脑机接口大会) on July 3, 2023, where Gao Xiaorong—the Tsinghua professor who figured prominently in this study—opined that BCI will be the venue for interacting with superintelligence[137]—a mega-development that, if feasible at all, would surely intensify the global debate between "boomers" and "doomers," i.e., those enamored and fearful of AI progress.

Finally, cognitive enhancement as a goal of Chinese BCI research was stated unambiguously in Chinese Communist Party "Guidelines" released in February 2024, underscoring the present study's main thesis.[138]

- The "Guidelines" also clearly define five research types: non-invasive restorative brain-computer interface research, invasive restorative brain-computer interface research, interventional brain-computer interface research, **augmentative brain-computer interface research**, and animal brain-computer interface research.
- The "Guidelines" clarify that **augmentative brain-computer interface** refers to brain-computer interface technology that enhances the perception, cognition, and motor abilities of users with normal body functions.

These aspirations offer clues about China's trajectory but are inadequate measures of progress. The present study tested the *credibility* of such statements by reviewing China BCI papers and patents. We found China's non-invasive BCI research to be comparable with that of other scientifically advanced nations and to be working to overcome obstacles to greater fidelity, throughput, and wider use. China's invasive BCI research, while historically behind its non-invasive efforts, has picked up the pace and is approaching global standards of sophistication.[139] That is, published Chinese BCI research is consistent with the stated goals of its vocal scientific community.

A second purpose of this study, beyond examining China's BCI enterprise, is to help manage the challenge it poses to competing nations by assembling in one place a record of the scientists and organizations that make up its infrastructure. As with earlier CSET studies,[140] the aim is always to ingest the data into a watchboard to monitor Chinese S&T development for security, safety, and ethical issues, and to engage China on opportunities for mutual benefit.

China's BCI research, beyond medical uses, poses three types of risk: (1) medium-term challenges from enhanced productivity and warfighting capability that emerge from tighter integration between humans and computers; (2) BCI's role over the longer term in facilitating a synthesis of human and machine intelligence that could snowball into a form of general intelligence; and (3) ethical and privacy concerns arising from China's use and export of BCI devices. These risks are amplified by the likelihood that Chinese institutions researching brain-computer technology, and the scientists affiliated with them, are under more pressure than their foreign counterparts to align their research with the expectations of their government sponsors.[141]

The suite of risks posed by the merger of human and artificial intelligence should be monitored by a global consortium drawing on resources from government and the private sector to provide U.S. policymakers timely and continuous updates on China's—and other nations'—progress in these strategic technologies.[142]

In the interim, we repeat here a standing offer to support any serious non-commercial U.S., UK, or other allied effort to create this needed capability.

Authors

Huey-Meei Chang is CSET's senior China S&T specialist, co-editor of *Chinese Power and Artificial Intelligence: Perspectives and Challenges* (New York and London: Routledge, 2023), and co-author of several papers on China's technology acquisition and development.

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[11] Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research."

[12] Qian Ma, et al., "Directly wireless communication of human minds via non-invasive brain-computer-metasurface platform," *Springer Open*, February 11, 2022, https://elight.springeropen.com/articles/10.1186/s43593-022-00019-x.

[13] Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research."

[14] See Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research" for an appendix of bilingual keywords related to cognitive enhancement.

[15] 2020 was the cut-off date for BCI data cited in the previous study by Hannas, Chang, Chou and Fleeger, July 2022. Papers published in 2023 were sourced externally, chiefly through Georgetown University's library.

[16] A "China" paper is defined as a paper where one or more authors claim affiliation with a China-based organization.

[17] Patrick A. Cutter, "The Shape of Things to Come: The Military Benefits of the Brain-Computer Interface in 2040," M.A. thesis submitted to the Air Command and Staff College, Air University, April 2015.

[18] "The goal of Augmented Cognition research is to create revolutionary human-computer interactions that capitalize on recent advances in the fields of neuroscience, cognitive science and computer science." Dylan D. Schmorrow and Leah M. Reeves, eds., *Foundations of Augmented Cognition*, Springer, 2007, XII.

[19] D.P. Williams, M. Couillard and Samantha Dugelay, "On Human Perception and Automatic Target Recognition: Strategies for Human-Computer Cooperation." *22nd International Conference on Pattern Recognition: NATO Science and Technology Organization*, (2014): 4695.

[20] Elsa B. Kania, "Minds at War: China's Pursuit of Military Advantage through Cognitive Science and Biotechnology," PRISM 8.3, January 2020. Margaret Kosal and Joy Putney, "Neurotechnology and international security: Predicting commercial and military adoption of brain-computer interfaces (BCIs) in the United States and China," *Politics and the Life Sciences*, 2022.

[21] The batch was made up of foundational papers identified in the authors' prior peer-reviewed studies (Hannas, Chang, Aiken, and Chou, "China AI-Brain Research;" Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research"). "Key authors" included 48 identified in the authors' prior research and another 28, who (co)authored two or more titles in the starting list of 141. New selections were limited to studies published between 2020 and 2023.

[22] I.e., 103 or 21.8 percent of the 473 candidate papers were (independently) rejected by both SMEs as "off-topic" during the second run that used "on-topic" papers as its starting point, compared to 93.2 percent rejected during the first run that was based solely on keyword choices.

[23] Prior studies on Chinese AI by this paper's authors were based entirely on Chinese academic papers and Internet research. Patents were not addressed at the time due to a lack of resources.

[24] The CSET unified patents dataset includes information on more than 82 million patents worldwide merged from multiple patent data sources, specifically the Lens, 1790 Analytics and EPO's PATSTAT.

[25] Second authors who "shared equally" in the work usually claimed the same primary affiliation as the first author.

[26] Tianjin's Nankai University and Haihe Laboratory, while not prominent in the published studies count, have other features that merit their inclusion in the narrative below, hence they are depicted on the map as well.

[27] The Pazhou Lab or "Guangdong Artificial Intelligence and Digital Economy Laboratory" (人工智能与数字经济广东省实验室), was established by the provincial government in 2020 and is "committed to advancing the fundamental research of AI." Its appearance in this survey of Chinese BCI institutes underscores the link between AI and BCI, https://www.pazhoulab.com/. See Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research."

[28] "2021-2022 BAAI AI Frontiers" (2021-2022 年度智源人工智能前沿报告), (BAAI, December 2021), 106, http://www.ncsti.gov.cn/kjdt/kjrd/202112/P020211231640762390337.pdf.

[29] Ye Dawei is now at Huazhong University of Science and Technology in Wuhan, https://ieeexplore.ieee.org/author/37086347850.

[30] Xu Wei, "China's First Wireless Brain-Computer Interface Chip for Animals Goes on Display in Shanghai," *Yicai*, April 19, 2021, https://www.yicaiglobal.com/news/china-first-wireless-brain-computer-interface-chip-for-animals-goes-on-display-in-shanghai.

[31] "Zhang Gong Inaugurated the Haihe Laboratory of Brain-Computer Interaction and Human-Computer Integration" (张工为脑机交互与人机共融海河实验室揭牌), *Tianjin Daily* (天津日报), March 29, 2023, http://tj.news.cn/gov/tjld/zhanggong/2023-03/29/c_1129474456.htm; "Brain-Computer Interaction and Human-Computer Integration Haihe Laboratory Unveiled" (脑机交互与人机共融海河实验室揭牌), *Tianjin Daily* (天津日报), March 29, 2023, https://www.tj.gov.cn/sy/tjxw/202303/t20230329_6152971.html. Gu Xiaosong is with the Chinese Academy of Engineering (CAE). Ming Dong (see below) is the laboratory's executive director, http://mctu.tju.edu.cn/info/1193/1324.htm.

[32] Literally "chokehold" (卡脖子) or "chokepoint" problems. This usually refers to technologies important to China but which China has not fully mastered. Computer chips and aerospace engines are examples.

[33] For information on the Hangzhou center and laboratory, see: https://bmci.hdu.edu.cn/7484/list.htm; https://computer.hdu.edu.cn/2018/0523/c6756a139129/page.htm.

[34] Qiao Renming (乔仁铭) and Chen Bin (陈彬), "The world's first non-human primate interventional brain-computer interface test was successful" (全球首例非人灵长类动物介入式脑机接口试验成功), *China Science Daily* (中国科学报), May 6, 2023, https://news.sciencenet.cn/htmlnews/2023/5/500018.shtm.

[35] Li Dong (李东), Han Kangni (韩康妮), and Huang Xin (黄辛), "Ruijin Hospital establishes brain-computer interface and neuromodulation center" (瑞金医院成立脑机接口及神经调控中心), *China Science Daily* (中国科学报), December 12, 2020, https://news.sciencenet.cn/htmlnews/2020/12/450072.shtm.

[36] Josh Ye, "Shanghai hospital clears ethical reviews for chip brain implant treatment for depressed patients," *South China Morning Post*, 15 December 2020, https://www.scmp.com/tech/science-research/article/3114029/shanghai-hospital-clears-ethical-reviews-chip-brain-implant.

[37] For information on South China University of Technology, see: http://www2.scut.edu.cn/bci/18562/list.htm; and https://www2.scut.edu.cn/bci/2018/0910/c18576a284387/page.htm.

[38] Liu Qian (刘茜), Chen Jianqiang (陈建强), Zhao Hui (赵晖), "Brain Talker: The Era of Brain Science Is Coming" (脑语者：脑科学时代正在走来), *Guangming Daily* (光明日报), January 18, 2020, https://news.sciencenet.cn/htmlnews/2020/1/434964.shtm; Liang Yu, ed., "China Unveils Brain-computer Interface Chip," *Xinhua*, May 18, 2019, http://www.xinhuanet.com/english/2019-05/18/c_138069590.htm.

[39] Li Xuanmin and Qi Xijia, "China develops self-made brain-computer interface chip, curbing tech 'bottleneck' amid U.S. tensions," *Global Times*, April 27, 2021, https://www.globaltimes.cn/page/202104/1222236.shtml.

[40] "216 keys! The world's largest instruction set high-speed non-invasive brain-computer interface system is released in Tianjin" (216 键！全球最大指令集高速非侵入式脑机接口系统在天津发布), *Tencent Net* (腾讯网), May 20, 2023, https://new.qq.com/rain/a/20230520A02H6D00?no-redirect=1. The Chinese term 指令集 / "instruction set" refers to computer instructions that respond to a user's fixation on a "targeted" square in a matrix of 216 (18 x 12) squares. Each square has a letter, number, syllable, or keyboard command assigned to it.

[41] For information on Tsinghua's BCI Lab, see: Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research."

[42] See: Artificial Intelligence Industry Alliance (中国人工智能产业发展联盟), "White paper on the application of brain-computer interface technology in the medical and health field" (脑机接口技术在医疗健康领域应用白皮书), July 2021, 43; Dan Zhang, Huaying Song, Rui Xu, Wenjing Zhou, Zhipei Ling, Bo Hong, "Toward a Minimally Invasive Brain-computer Interface," *NeuroImage* 71 (2013): 30-41.

[43] "2023 'Science Innovation China' Brain-Computer Interface Industry-Academic Integration Seminar Concluded Successfully" (2023 '科创中国' 脑机接口产学融合研讨会圆满落幕), *Tencent Net* (腾讯网), October 9, 2023, https://new.qq.com/rain/a/20231009A09KAT00; "Zhejiang University Double Brain Center Brain Computer PI Recruitment" (浙江大学双脑中心脑机 PI 招聘), January 21, 2023, http://www.bbmi.zju.edu.cn/2021/0316/c43507a2268034/page.htm.

[44] Formally known as the "Ministry of Education (MOE) Frontier Science Center for Brain Science and Brain-Machine Integration" (教育部脑与脑机融合前沿科学中心).

[45] Introduction to Zhejiang University's School of Brain Science and Brain Medicine: http://www.neuroscience.zju.edu.cn/2020/0506/c45491a2092569/page.htm.

[46] "Introduction to the scientific research team of the School of Computer Science" (计算机学院科研团队情况介绍表), http://www.cs.zju.edu.cn/_upload/article/files/d4/45/e46a2ca6469693738d84d1fffc3f/cbe13c0b-0942-45cb-b043-164256b0e7c8.pdf.

[47] Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research."

[48] Papers had as few as one author and as many as a dozen or more, with three authors being the mean.

[49] Authors with non-China primary affiliations were captured in different columns of the spreadsheet.

[50] Lu Baoliang's surname "吕" is properly spelled "Lv" in China's *pinyin* romanization but appears as "Lu" in most (but not all) publications.

[51] Jung is also affiliated with the Swartz Center for Computational Neuroscience, University of California San Diego, CA, USA.

[52] "The first China Brain-computer Interface 'Huanao Award' was announced!" (首届中国脑-机接口"华瑙奖"重磅揭晓!), BrainNews, July 5, 2023, https://mp.weixin.qq.com/s/oEvx2wHcgBFekhKWrrlSNA.

[53] A review of Zhao's published work supports this judgment. See: https://www.researchgate.net/scientific-contributions/Guoguang-Zhao-2216516722.

[54] The chip was developed jointly by Tianjin University and the China Electronics Corp. (中国电子信息产业集团), https://www.sohu.com/a/315191613_99992021.

[55] CHEN Xiaogang (陈小刚), JI Bowen (吉博文), JIN Jing (金晶), LI Jingcong (李景聪), LI Mengfan (李梦凡), LI Rui (李锐), PAN Jiahui (潘家辉), PENG Yong (彭勇), WANG Kun (王坤) and XU Minpeng (许敏鹏).

[56] CAI Xinxia (蔡新霞), CHEN Xun (陈勋), DUAN Feng (段峰), FU Yunfa (伏云发), GAO Xiaorong (高小榕), HE Huiguang (何晖光), HU Dewen (胡德文), KANG Xiaoyang (康晓洋), KONG Wanzeng (孔万增), LI Luming (李路明), LI Xiaojian (李骁健), LI Yuanqing (李远清), LIU Jingquan (刘景全), LU Baoliang (吕宝粮), MING Dong (明东), PAN Gang (潘纲), PAN Jiahui (潘家辉), WANG Xingyu (王行愚), WANG Yiwen (王怡雯), ZHOU Zongtan (周宗潭).

[57] Based on relative standing among first authors, authors overall and the Huanao Award.

[58] See Chen Xiaogang's CV:
https://www.bme.org.cn/rcdw/fyjy/9cf34f2e235b4953a764f0c7e9574f32.htm;
https://ieeexplore.ieee.org/author/37085431062.

[59] See Chen Xun's CV: https://eeis.ustc.edu.cn/2020/0720/c2648a439187/page.htm.

[60] A NYSE-listed Chinese firm established in 2013 manufacturing smart wearable technology. Prior to 2021, the company's English name was Huami Corporation, https://www.zepp.com/press-release/huami-corporation-announces-name-change-to-zepp-health.

[61] "Zepp Health and the Advanced Research Institute of the University of Science and Technology of China jointly build the 'Brain-Computer Intelligence Joint Laboratory'," (华米科技与中科大先研院共建'脑机智能联合实验室'), http://news.ustc.edu.cn/info/1056/70794.htm.

[62] "The first China Brain-computer Interface 'Huanao Award' was announced!" (首届中国脑-机接口"华瑙奖"重磅揭晓!), BrainNews, July 5, 2023, https://mp.weixin.qq.com/s/oEvx2wHcgBFekhKWrrlSNA.

[63] "Three professors from Tsinghua-IDG/McGovern Institute for Brain Science were selected into the 2021 'China's Highly Cited Researchers' list" (清华-IDG/麦戈文脑科学研究院三位教授入选 2021 "中国高被引学者" 榜单), April 14, 2022, http://mcgovern.life.tsinghua.edu.cn/ch/infoshow-2395.html.

[64] Hu Dewen joins PLA: https://www.nudt.edu.cn/xy/xyfc/b11c6b247d5b40499f6bf62895d326b6.htm; Hu Dewen's biography: https://ieeexplore.ieee.org/author/37271079500.

[65] "Professor Hu Dewen from the National University of Defense Technology gave an academic report on 'Pattern Recognition of Brain Information'" (国防科技大学胡德文教授做"大脑信息的模式识别"的学术报告), July 26, 2020, https://www.scholat.com/teamwork/showPostMessage.html?id=8209.

[66] See Jin Jing's brief biography: https://ieeexplore.ieee.org/author/37965693000.

[67] For further details on Jin Jing see: https://cise.ecust.edu.cn/2021/0315/c12977a123830/page.htm.

[68] https://faet.fudan.edu.cn/e4/55/c23898a255061/page.htm.

[69] He Liping (贺梨萍), "Li Xiaojian from Shenzhen Advanced Institute: China is not lagging behind in the global competition for brain-computer interfaces" (深圳先进院李骁健：脑机接口全球竞赛， 中国不落后), *The Paper* (澎湃新闻) September 7, 2021, https://m.thepaper.cn/newsDetail_forward_14376847. Joe Tsien's career at U.S. institutions, the circumstances surrounding his nickname "father of smart rats," and his convoluted and controversial relationship with U.S. authorities is detailed in Daniel Golden and Jeff Kao, "A Visionary without a Country," *Propublica*, January 20, 2022, https://www.propublica.org/article/a-visionary-without-a-country.

[70] See Li Xiaojian's brief biography at: http://bcbdi.siat.ac.cn/index.php/member/showMember/nid/13.shtml.

[71] "Another major breakthrough in brain-computer interfaces! Shenzhen Institute of Advanced Technology: Li Xiaojian and team release latest results in the Nature sub-journal" (脑机接口又一重大突破！深圳先进院李骁健及合作团队在 Nature 子刊发布最新成果), sourced from: *Shenzhen Economic Daily* (深圳商报), September 18, 2022, https://www.toutiao.com/article/7144668280785994240/?&source=m_redirect.

[72] https://www2.scut.edu.cn/bci/18571/list.htm. Li Yuanqing is also vice-director of the Pazhou Lab (琶洲实验室) and founder of the Guangdong BCI/AI company South China Brain Control Guangdong Intelligent Technology (华南脑控（广东）智能科技有限公司), run jointly with the South China University of Technology and iFlytek, http://www.ihnnk.com/?s=About.

[73] See Lu's CV at: https://bcmi.sjtu.edu.cn/home/blu/. Lu founded "Emotion Helper" (零唯一思) in 2021, a company aimed at improving people's emotional health, i.e., "affective BCI," https://www.emotionhelper.com/.

[74] For more information on Ming Dong, see: https://faculty.tju.edu.cn/MingDong1/en/index.htm; http://mctu.tju.edu.cn/info/1193/1324.htm.

[75] https://www.scholat.com/panjiahui.

[76] The center's (中心) name appears in some sources as a "research group" (小组).

[77] http://ss.scnu.edu.cn/a/20190602/1801.html.

[78] "Introduction to the institutes" (研究所介绍): https://computer.hdu.edu.cn/6750/list.htm.

[79] See Peng Yong's bio at: https://sunseaiu.github.io/; https://ieeexplore.ieee.org/author/37086153359. For dates of overseas study, see also: https://bcmi.sjtu.edu.cn/~pengyong/%E5%BD%AD%E5%8B%87-%E7%AE%80%E5%8E%86word.pdf.

[80] Jose C. Principe is Distinguished Professor of Electrical and Computer Engineering at the University of Florida with expertise in signal processing and BCI. https://www.ece.ufl.edu/people/faculty/jose-c-principe/.

[81] See Yiwen Wang's biographical information at: https://ieeexplore.ieee.org/author/37337396900; https://seng.hkust.edu.hk/about/people/faculty/yiwen-wang.

[82] See Dongrui Wu's biographical information at: https://ieeexplore.ieee.org/author/37693329600.

[83] For information on Wu's BCI lab, see: https://lab.bciml.cn/.

[84] See Xu's biographical information at: http://amt.tju.edu.cn/portal/teachers/getperson/id/32/sId/2/bId/2.html and https://ieeexplore.ieee.org/author/37850640000.

[85] Chu Daye, "Chinese companies ramp up for emerging BCI technology, ready for larger market," *Global Times*, November 28, 2022, https://www.globaltimes.cn/page/202211/1280640.shtml.

[86] "Brain-computer Interface Technology Development and Application Research Report (2023)" (脑机接口技术发展与应用研究报告 (2023)), China Academy of Information and Communications Technology and Brain-computer Interface Industry Alliance (中国信息通信研究院脑机接口产业联盟), December 26, 2023, 4, https://perma.cc/GJ5Q-D5FR; "Analysis of the Ten-billion Dollar Market for Brain Science" (脑科学百亿市场解析), DeepTech (深科技), April 25, 2021, https://www.sohu.com/a/462880163_354973.

[87] Hai Ruojing (海若镜), "Brain-computer interface is very close to curing depression and paralysis, but is far from digital immortality" (脑机接口，离治抑郁、瘫痪很近，离数字永生很远), *36Kr New Trend*, October 11, 2023, https://www.36kr.com/p/2468019557816456.

[88] "An inventory of Chinese BCI companies most worthy of cooperating with in 2023" (2023 中国最具商业合作价值的脑机接口领域企业盘点), *Sohu.com*, June 1, 2023, https://www.sohu.com/a/681171075_121203063.

[89] Hai Ruojing, "Brain-computer interface is very close to curing depression and paralysis, but is far from digital immortality."

[90] NeuraMatrix's two founders are Bai Shuo (白硕, CAS) and Zhang Milin (张沕琳, Tsinghua). They "have been conducting related academic research at the University of Pennsylvania and the Max-Planck Institute in Germany since 2010." See "Brain-computer interface platform company "NeuraMatrix" completed RMB 100 million in Series A financing" (脑机接口平台公司宁矩科技'(NeuraMatrix)'完成亿元人民币 A 轮融资), November 22, 2021, https://www.36kr.com/p/1491487908933765; http://www.neuramatrix.com.cn/.

[91] For details, see: https://www.zhipin.com/web/common/security-check.html?seed=1aDuhcMF3ReI%2FKyNnmMbmiStL86K4DPH10nd1tPYVN0%3D&name=3c433761&ts=1710441353752&callbackUrl=%2Fgongsi%2F53d6544bec8142521XB43du4FVE%7E.html&srcReferer=.

[92] Fang's CV:
http://www.cebsit.ac.cn/sourcedb_cebsit_cas/zw/rck/Members/202007/t20200723_5642966.html;
http://sourcedb.nanoctr.cas.cn/yw/rc/200906/t20090602_252658.html.

[93] Qiao Yanwei (乔燕薇), "Song Qi, the former CEO of Keya Medical, becomes the CEO of the new company Zhiran Medical; 'invasive brain-computer interface' becomes the next direction." (原科亚医疗 CEO 宋麒出任新公司智冉医疗 CEO, '侵入式脑机接口' 成为下一站方向), *Leiphone.com* (雷锋网), April 19, 2023

[94] Hai Ruojing, "Brain-computer interface is very close to curing depression and paralysis, but is far from digital immortality."

[95] https://baike.baidu.com/item/北京脑科学与类脑研究中心/22450631.

[96] For details on company, see: https://www.fy35.com/company/14974327.html.

[97] "Intelligent Brain-Computer System Enhancement Program officially launched" ('智能脑机系统增强计划' 正式启动), *ZGC Group* (中关村发展集团), April 14, 2023,
https://zgcgroup.com.cn/zgcadmin/home/content/index.html?id=3176&cate=15.

[98] Company details are at: https://www.stairmed.com/.

[99] For Zhao's and Li's CVs, see: http://www.cebsit.cas.cn/yjz/zzt/ry/;
http://www.cebsit.cas.cn/yjz/qnyjy/lx/ry/.

[100] Qian Tongxin (钱童心), "Chen Tianqiao invested another 1 billion Yuan to support AI brain science and three brain-computer interface clinical implants have been completed" (陈天桥再投 10 亿元支持 AI 脑科学，脑机接口临床已完成 3 项植入), Yicai.com (第一财经), July 6, 2023,
https://m.yicai.com/news/101800756.html. The full name of the Huashan facility is Frontier Laboratory of Applied Neurotechnology (应用神经技术前沿实验室).

[101] For more information, see: https://www.cheninstitute.org/.

[102] Company information is at: en.neuroxess.com. In an earlier CSET study ("China's Advanced AI Research"), the authors erroneously reported NeurXess co-founder 彭雷(PENG Lei) as 彭蕾 (PENG Lei).

Both were at Alibaba. The homophonous given name "Lei" is distinguished in Chinese by the "grass" radical (艹) on the second character.

[103] "NeuroXess completed RMB 97 million angel and Pre-A rounds of financing. All-star investors and consultants attended the grand opening ceremony" (脑虎完成 9700 万天使及 Pre-A 轮融资 全明星投资人、顾问天团参加盛大开业仪式), January 11, 2022, https://www.neuroxess.com/nx/news/213?env=product&lang=zh&post_id=213&type=post.

[104] "NeuroXess 'emerged' to fully support Chinese brain science" (脑虎科技'横空出世,' 全程支持中国脑科学), *Huanqiu.com* (环球网), January 14, 2022, https://quality.huanqiu.com/article/46OnnMH7FwG; see details on silk electrodes at: https://en.neuroxess.com/nx/product/slik-trode; Ni Sijie (倪思洁), "Tao Hu: 80 top publications in 10 years, convinced Chen Tianqiao in 1 hour" (陶虎: 10 年 80 篇顶刊, 1 小时说服陈天桥), *China Science Daily* (中国科学报), May 14, 2022, https://news.sciencenet.cn/htmlnews/2022/5/479024.shtm.

[105] "The Year of the Tiger welcomes an exciting new player in brain science: the story of the creation of NeuroXess" (虎年前迎来脑科学新锐：脑虎科技的创生故事), 芯语, January 11, 2022, https://www.eet-china.com/mp/a103651.html.

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[107]http://www.neuracom.com.cn/; Li Xinyu (李昕宇), "Wuhan company self-developed 'implantable brain-computer interface system,' the world's first 'bi-directional reading and writing' of brain electrical signals" (武汉企业自研'植入式脑机接口系统' 全球首创大脑电信号'双向读写'), *Changjiang Daily* (长江日报), https://finance.sina.com.cn/tech/internet/2023-08-31/doc-imzizvhm9930737.shtm.

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[109] BrainCo's website is at: https://www.brainco.cn/.

[110] "Brain-Machine Interface Firm BrainCo's Brain Robotics Hand Obtains FDA Certification," *Pandaily*, November 8, 2022, https://pandaily.com/brain-machine-interface-firm-braincos-brainrobotics-hand-obtains-fda-certification/.

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[112] Li Xiaojian's post-doctoral work included three years at the Medical College of Georgia and five years as assistant professor at Northwestern University, http://bcbdi.siat.ac.cn/index.php/member/showMember/nid/13.shtm.

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[114] "Major alliance founded, 9 units including Tsinghua University elected to board" (重磅联盟成立, 清华大学等 9 单位当选为副理事长单位), *Sohu.com*, February 11, 2023, https://www.sohu.com/a/639556571_773043.

[115] "Inaugural meeting of Brain-Computer Interface Industry Alliance successfully held in Beijing" (脑机接口产业联盟成立大会在京成功召开), *Sohu.com*, February 9, 2023, https://www.sohu.com/a/638787609_121181007.

[116] Xie Longfei (谢龙飞), "China's brain-computer interface research achieved serial results, experiments on humans and primates carried out" (中国脑机接口研究取得系列成果 目前已开展人体和灵长类动物实验), *ChinaNews*.com (中国新闻网), May 18, 2023, https://www.jwview.com/jingwei/html/m/05-18/541283.shtml.

[117] "Brain-Computer Interface Technology and Application Seminar and Brain-Computer Interface Industry Alliance Member Symposium successfully held" (脑机接口技术与应用研讨会暨脑机接口产业联盟会员座谈会成功举办), *Xi'an Jiaotong University News*, November 15, 2023, https://news.xjtu.edu.cn/info/1002/203365.htm.

[118] fNIRS is a non-invasive optical imaging technique that measures hemoglobin concentrations in the brain.

[119] fMRI is a brain imaging technique that measures small changes in blood flow to infer neural activity in an area.

[120] "P300" is an event-related potential (measured voltage change) that occurs approximately 300 milliseconds after a behaviorally salient stimulus. The "speller" is a device used to spell words (or select items from arbitrary lists) with brain waves.

[121] SSVEPs are brain signals that respond to visual stimulation at the same frequency or a harmonic, allowing the selection of items presented on a screen that oscillate at varying frequencies.

[122] "China completes world's first interventional BCI experiment on non-human primates," *Xinhua*, May 6, 2023, https://english.news.cn/20230506/e49f8dcb3f504e81a8ce2058cba38f1e/c.html.

[123] For comparison, the information rate of human speech (spoken, non-BCI) is 39 bits *per second*. Christophe Coupé, Yoon Mi Oh, Dan Dediu, Francois Pellegrino, "Different languages, similar encoding efficiency: Comparable information rates across the human communicative niche." *Sciences Advances*, 5, no. 9 (2019).

[124] See, for instance, Sebastian Nagel and Martin Spüler, (2019), "World's fastest brain-computer interface: Combining EEG2Code with deep learning," *PLoS ONE*, September 6, 2019.

[125] Of course, the calculus changes when considering clinical populations, such as paralyzed or "locked-in" individuals, for whom, e.g., BCI-enabled wheelchair control or communication via the use of BCI spellers have the potential to dramatically improve their quality of life. Yet, these applications were beyond the scope of this report and its focus on non-therapeutic BCI.

[126] See Paulk et al. for a description of recordings with an earlier version of the system permitting the simultaneous recording of hundreds of neurons. Angelique C. Paulk, Yoav Kfir, Arjun R. Khanna, Martina L. Mustroph, et al., "Large-scale neural recordings with single neuron resolution using Neuropixels probes in human cortex," *Nature Neuroscience*, 25 (2022): 252–263.

[127] Note: We used a whole-number country contribution methodology to count the collaborators. If one publication had authorship from two different countries, that publication was counted equivalently as one publication for each of those countries.

[128] Daniel H. Chou, "Revisiting China's Security Forces' AI Research Output," (CSET, June 2022), https://cset.georgetown.edu/article/revisiting-chinas-security-forces-ai-research-output/.

[129] Daniel H. Chou, "Revisiting China's Security Forces' AI Research Output."

[130] Ryan Fedasiuk and Emily S. Weinstein, "Universities and the Chinese Defense Technology Workforce," (CSET, December 2020), https://cset.georgetown.edu/publication/universities-and-the-chinese-defense-technology-workforce/.

[131] Ryan Fedasiuk and Emily S. Weinstein, "Universities and the Chinese Defense Technology Workforce."

[132] Dakota Cary, "Testimony before the U.S.-China Economic and Security Review Commission on 'China's Cyber Capabilities: Warfare, Espionage and Implications for the United States,'" (CSET, February 2022), https://cset.georgetown.edu/publication/dakota-carys-testimony-before-the-u-s-china-economic-and-security-commission/.

[133] Dakota Cary, "Testimony before the U.S.-China Economic and Security Review Commission on 'China's Cyber Capabilities: Warfare, Espionage and Implications for the United States'."

[134] Russia's score is unrepresentative; a single author–Andrzej Cichocki–was responsible for all 20 collaborations. Cichocki's multiple affiliations also skewed the Polish and Japanese distributions.

[135] Data for the year 2023 takes into account only part of that year.

[136] Hannas, Chang, Wang, Aiken, and Chou, "China AI-Brain Research;" Hannas, Chang, Chou and Fleeger, "China's Advanced AI Research."

[137] "The most important rein for holding this superintelligence in check." (牵制这种超级智能最重要的缰绳). Yang Yuehan (杨月涵), "Is there an 'iPhone moment' for brain-computer interfaces?" (脑机接口有没有'iPhone 时刻'), *Beijing Business Today* (北京商报), July 5, 2023, http://finance.china.com.cn/industry/20230705/6005433.shtml.

[138] Artificial Intelligence Ethics Subcommittee of the National Science and Technology Ethics Commission (国家科技伦理委员会人工智能伦理分委员会), "'Ethics Guidelines for Brain-Computer Interface Research' Released" ("脑机接口研究伦理指引"发布), MOST (科技部), February 2, 2024, translated by CSET, https://cset.georgetown.edu/publication/china-bci-ethics/, our emphasis.

[139] A study by Zhou Jie (周洁), Wang Chunjia (王淳佳) and Zhang Qian (张倩), all with the Intellectual Property and Innovative Development Center of the China Academy of Information and Communications Technology, (中国信息通信研究院知识产权与创新发展中心), claims China surpassed the United States in 2015 in the number of applied patents for invasive BCI electrode technology and has been widening the gap ever since. "Development trend analysis of implantable brain-computer interface electrode technology from patent perspective" (专利视角下植入式脑机接口电极技术发展趋势分析), *Information and Communications Technology and Policy* (信息通信技术与政策), 49, no. 3, (2023): 61-67.

[140] Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research."

[141] John Chen, personal communication, January 2024. Most Chinese papers reviewed in this study acknowledge support from China's National Natural Science Foundation, National Key Research and Development Project, National Basic Research Program of China, and sundry other government foundations at the state, provincial and municipal levels.

[142] Hannas, Chang, Chou, and Fleeger, "China's Advanced AI Research," 44, offers a sketch of a minimalist open-source technology monitoring program. Broader projects are being discussed with U.S. and UK policymakers.