LANDSCAPE OF
BRAIN RESEARCH IN INDIA

A report by itihaasa Research and Digital
2018

itihaasa
Research and Digital

CONTENTS

FOREWORD

We have come a long way since Homo Sapiens - our species - first made an appearance about two hundred thousand years ago. Stone tools were first used by Australopithecus Africanus about 3.4 million years ago, and fire was first controlled by Homo Erectus about six hundred thousand years ago. The start of the modern scientific revolution in the mid-16th century began with the publication of Nicolaus Copernicus' On the Revolutions of the Heavenly Spheres, the seminal work on the heliocentric theory. Ever since the advent of the steam engine in 1765, we have witnessed a continuous stream of technology inventions that has improved human productivity. According to a report by Barclays analysts, if human productivity was 100 units in 1765 it is increased to 3000 units today. In fact, the last five decades have seen an increase in human productivity from about 1500 units to 3000 units. And this steep increase coincides with the adoption of IT including personal computing, software, Internet, e-mail, mobile communications etc. The next phase, the fourth industrial revolution, is powered by advances in AI/ML and brain science and is blurring the lines between the physical, digital, and biological domains.

Let us look at the evolution of world from the economic lens. Robin Hanson, a researcher at the Future of Humanity Institute in Oxford University, modeled the step change in economic activity. If humans continued as a hunter – gatherer society, then the world's economy will double every 224,000 years. If we continued as a purely farming society, then the world economy doubles every 909 years. And if we continue as an industrial society - the first three industrial revolutions - then the world economy will double every 6.3 years. We can imagine the next economic shift powered by the science and technological advances of the fourth industrial revolution.

Where is India placed in shaping this next revolution? I am optimistic for India. It is heartening to note that India is continuing on the path of nurturing science and technology advancement, and using the resultant knowledge for the benefits of its citizens. However, there is more that should be done. India invests 0.8% of its GDP in research – 0.6% is by the Government and 0.2% is from private contribution. Countries like China and South Korea invest 4% of GDP in research and the USA 2.7%. We should increase research spending to 3% of GDP – 1.5% from Government and 1.5% from private sources. Private funding has played an important role in the transformation of emerging nations. For example, in the mid-2000s about 65% of Taiwan's R&D was from private sector funding up from about 30% in the past. India is at a point in history where private funding can supplement government funding in research, and this includes philanthropy. This may also be the time to tweak the current rules on corporate social responsibility that mandates that 2% of average net profit be spent on specified social activities. What if instead, 1% of such funds can be used to fund science and technology research that shapes our future? Another current development that is heartening to note is the revival in philanthropic funding for Indian science. I believe that this will only grow in future.

The Government is seized of the importance of building national capability in AI. The Indian educational institutions and research community, industry and the start-up community are equally enthused about this task. India has a strong foundation in AI/ML and building one in brain science. If we treat this as a national priority, we will succeed in building world-class capabilities like we have successfully done in domains like IT services and space research. I hope that the landscape studies of AI/ML and brain research in India will identify important focus areas of research and translational research and help spark a dialog among researchers, policy makers, industry and philanthropists in India.

Let me end on a philosophical note. While artificial general intelligence - that is human-like intelligence - is still only an aspirational goal of AI, it may be prudent for us to deliberate on what it all means for furthering of human knowledge. I. J. Good, chief statistician of Turing's code breaking team wrote in 1965, "Let an ultra-intelligent machine be defined as a machine that can far surpass all the intellectual activities of any man however clever. Since the design of machines is one of these intellectual activities, an ultra-intelligent machine could design even better machines; there would then unquestionably be an "intelligence explosion," and the intelligence of man would be left far behind. Thus, the first ultra-intelligent machine is the last invention that man need ever make, provided that the machine is docile enough to tell us how to keep it under control." Will we ever reach such a point of technological singularity? Will human ingenuity and spirit triumph? Only time will tell. We must nevertheless move forward on this journey enthusiastically and judiciously.

Kris Gopalakrishnan

Chairman itihaasa Research and Digital, Co-founder Infosys

EXECUTIVE SUMMARY

This report provides insights into the current landscape of brain research in India. It is based on primary interviews of 31 neuroscience researchers. Our objective for this study is to provide a nucleus for starting a dialogue among stakeholders and catalyzing concrete action plans for nurturing brain research in India.

Neuroscience is the study of neurons (the cells that make up the brain) and neural circuits. A sub-discipline is computational neuroscience which is the study of information processing properties of the brain. There are about 500 to 1000 researchers in neuroscience in India, and the number of principal investigators (who head labs and teams of researchers) in neurosciences is between 100 and 200. There are about 15 to 30 computational neuroscience principal investigators. Many of the national institutes of importance including Indian Institute of Science (IISc), Indian Institutes of Technology (IITs), NIMHANS, etc.; research centers like National Centre for Biological Sciences (NCBS), Institute for Stem Cell Biology and Regenerative Medicine (inStem), National Brain Research Centre (NBRC), etc.; and universities like University of Hyderabad, University of Allahabad, etc. have a research program in neuroscience.

In India, Centre of Behavioral and Cognitive Sciences (CBCS), University of Allahabad; Centre for Neural & Cognitive Sciences, University of Hyderabad; Centre for Cognitive Science, IIT-Gandhinagar; School of Cognitive Science, Jadavpur University; Indian Institute of Speech and Hearing, Mysore and IIT Kanpur offer master's programs. The number of neuroscience researchers in India is about 30X lesser than their numbers in the USA. There is a unanimous recommendation from researchers to increase the number of neuroscience students in India.

Research in neuroscience in India largely falls into three sub-domains (1) cognitive neuroscience (study of the mechanisms underlying cognition), (2) systems neuroscience (study of the function of neural circuits and systems), and (3) computational neuroscience. Our landscape study revealed that Indian researchers are inspired to find answers to some of the challenging problems in neuroscience.

- Modeling sensory (vision, speech, smell, etc.) and multisensory perception in humans
- Comprehending human abilities like attention, learning, causality, decision making, language, etc.
- Modeling how the brain works at multiple levels; cellular, network (of cells) level, etc.
- Brain inspired computational modeling techniques
- Brain inspired hardware architecture
- Developing alternative and better techniques to study the brain

Neuroscience is inherently multidisciplinary, and Indian researchers often forge collaborations with researchers with complementary expertise. About three fourths of the researchers we interviewed as part of the study had collaborations with researchers in universities and institutions other than their own. Indian researchers collaborate more with international researchers than with fellow Indian researchers. Clinicians are a most sought-after category of Indian collaborators.

Indian neuroscience researchers often require funding support from organizations other than their parent universities or research institutions. Department of Biotechnology (DBT) and Department of Science and Technology (DST) of the Government of India, Ministry of Human Resources Development (MHRD) of the Government of India, The Wellcome Trust DBT India Alliance, Pratiksha Trust, and Tata Trusts are among the largest sources of funds for brain research.

A majority of researchers believe that good quality research publications and subsequent citations are an important measure of impact of research. The next most important impact measure seems to be the ability to attract and place doctoral students.

There have been nationwide neuroscience initiatives started since 2011 in countries like China, Europe, Israel, Japan, and USA. Our analysis shows that over the last few years, India produces around 2% of the annual world research papers in neuroscience. USA as compared to India, produced 19 times the number of citable documents and they were cited 36 times more often.

One-fourth of the researchers we spoke to had active collaborations with industry, or had collaborated with industry in the past, or in preliminary discussions to collaborate. Less than one-fourth of the researchers feel that a startup is likely within the next two years. The main reasons for relatively lesser number of industry collaborations is due to the fact that most of the brain research in India is basic in nature, and the number of principal investigators is not as high as in other regions of the world to provide a larger basket of basic research output. We believe that it will take some time before there is an increase in translational research which may trigger more industry collaborations and startup activity. We foresee brain research spawning applications in healthcare & wellness, brain inspired computing systems, and other industries like automotive, education, consumer marketing, etc.

There is a broad convergence among Indian researchers that in the future, neuroscience will inspire the future developments in Artificial Intelligence and Machine Learning (AI/ML). A few salient themes that emerged from our discussions with researchers on AI/ML and neuroscience include

- Current AI/ML has its roots in an older understanding of the brain
- AI/ML can learn from the higher-level cognitive abilities of the brain
- AI/ML can also learn from the workings of the brains of other smaller species
- AI/ML specific computer architectures
- AI/ML can mimic brain when computing hardware is made of biomaterials

The study has identified four recommendations for strengthening the brain research ecosystem in India.

- Increase the number of neuroscience research students in India by attracting and ramping up the numbers of principal investigators, developing a strong graduate and undergraduate program, and offering intensive summer schools to train master's students in other disciplines in neuroscience

- Develop a strong multi-disciplinary research ecosystem in India by having institutional mechanisms to foster closer collaboration between universities, research institutions and medical universities, building the right incentive structures for interdisciplinary research and creating national facilities of computing infrastructure for neuroscience
- Adopt a consortium or network model such as a consortium on modeling the cellular level of the brain function, create a centre with a focus on understanding the whole system and one disease and continue to strengthen the role of a trusted intermediary (such as C-CAMP) for both researchers and industry
- Collaborate on global initiatives & platforms for sharing data so as to make research databases and tools accessible for neuroscientists worldwide, and integrate ethics and neuroscience

This is an opportune moment for India to get firmly plugged into international research initiatives, and should consider declaring a “decade of the brain” initiative to accelerate the ramp up of brain research in India.

1. INTRODUCTION

India has leapfrogged in building a world class capability in information technology (IT). The capability in IT has powered India's economic development in the past three decades. IT now contributes to 9.3% of India's GDP according to the Ministry of Electronics and Information Technology, Government of India[1]. While this is a significant achievement, India cannot afford to be complacent since IT is evolving rapidly. India has realized the impact of this change and is investing in the just emerged IT domains of artificial intelligence and machine learning (AI/ML). While the jury is still out on how well India has taken advantage of its dominant position in IT to acquire a capability in AI/ML, there is another change taking place. A new domain is advancing at an accelerating pace in parallel. It looks promising to advance quality of human life, and also enhance IT. This new domain is neuroscience (study of neurons the cells that make up the brain and neural circuits) with its sub-domain computational neuroscience (study of information processing properties of the brain).

The importance of brain research cannot be emphasized better than Patricia S. Churchland and Terrence J. Senjnowski in the 25th year anniversary preface of their classic book The Computational Brain.[2]

"There is a general feeling that the major advances being made in our understanding of the brain and the dramatic impact of deep learning and TD (temporal differences) learning on AI has led us to a tipping point. The current network models are based on what we knew about the brain in the 1960s. The next generation of neural network models will include many more brain systems and be based on a much better understanding of brain architecture and neural plasticity that covers a wider range of time scales. This has been accelerated by the BRAIN Initiative and other international brain programs including the European Human Brain Project and the Chinese Brain Project. The irony is that many of the machine learning algorithms that are now used to analyze big neuroscience data were inspired 30 years ago by the brain itself."

Indian researchers have been working in neuroscience from the 1970s. The current research in brain science is providing the nucleus for building a world-class capability in this domain. This study provides a current landscape of brain research in India. It is a first of its kind study, and is based on interviews we had with 31 neuroscience researchers (See Appendix).

Our objective for this study is to provide a nucleus for starting a dialogue among stakeholders that results in concrete action plans to significantly move the needle in brain research in India.

The report is organized as follows. Section 2 provides the state of brain research in India. Section 3 analyzes the brain research initiatives in other countries and the current collaborations of Indian researchers. Section 4 looks at the state of translating Indian neuroscience research into applications. Section 5 analyzes the connections between neuroscience, computational neuroscience, and AI/ML. Section 6 provides a set of recommendations to strengthen the brain research ecosystem in India.

1 http://meity.gov.in/content/fact-sheet-it-bpm-industry
2 The Computational Brain 25th Anniversary Edition by Patricia S. Churchland and Terrence J. Senjnowski. MIT Press, 2017. pp. xiv

2. BRAIN RESEARCH IN INDIA

In this section we provide an overview of brain science and its evolution in India. Brain science is a phrase increasingly used to refer to neuroscience and related sciences. This includes cognitive neuroscience, systems neuroscience, and computational neuroscience. We also estimate the number of neuroscience and computational neuroscience researchers in India based on the expert estimates, and triangulate it with secondary data. We touch upon the master's program in neuroscience in India. A detailed description of the focus areas and projects for Indian researchers in neuroscience follows. We then focus on two contextual facets of neuroscience research in India – multidisciplinary nature and funding sources. And to complete this section, we look at how researchers measure impact of their research.

2.1. What is neuroscience?

Neuroscience is a multidisciplinary branch of biology that combines physiology, anatomy, molecular biology, developmental biology, cytology (study of the structure and function of cells), mathematical modeling, computer science, electrical and other engineering, and psychology to understand the fundamental and emergent properties of neurons and neural circuits[3]. Neuroscience helps us to unravel the biological basis of learning, memory, behavior, perception, and consciousness. Neuroscience is often slated as the "ultimate challenge of the biological sciences" in the 21st century[4].

Three important sub-disciplines in neuroscience include[5]

- Cognitive Neuroscience: The study of the mechanisms underlying cognition with a specific focus on the neural substrates of mental processes.
- Systems neuroscience: The study of the function of neural circuits and systems.
- Computational neuroscience: The study of brain function in terms of the information processing properties of the structures that makes up the nervous system. It also refers to the use of computer simulations and theoretical models to study the function of the nervous system

The focus of Indian research covers all the three sub-domains of cognitive neuroscience, systems neuroscience, and computational neuroscience.

Modern multidisciplinary neuroscience traces its origins to the neuroscience research program weaving biology, chemistry, physics, and mathematics that was started within the Biology Department at the Massachusetts Institute of Technology in the 1950s by Francis O. Schmitt.

2.2. Neuroscience in India

Neuroscience research in India has seen growth from the 1970s[6]. The National Institute of Mental Health and Neurosciences (NIMHANS) with a predominantly clinical focus was established in 1974. In the same year, an International Symposium on Central Synaptic Transmission held at Central Drug Research Institute, Lucknow. This was probably among the early conferences in

3 https://en.wikipedia.org/wiki/Neuroscience
4 Principles of Neural Science Fifth edition by Eric R. Kandel. McGraw-Hill Education, 2012
5 https://en.wikipedia.org/wiki/Neuroscience
6 http://neuroscienceacademy.org.in/history.php

neuroscience in India. It took a decade more for the formation of The Indian Academy of Neurosciences, the primary association for neuroscience researchers in India. There are currently over 900 members of the Indian Academy of Neurosciences, a majority of them Indian[7]. Based on researchers' estimates in our study, there are about 500 to 1000 researchers in neuroscience in India, and the number of principal investigators (who head labs and teams of researchers) in neurosciences between 100 and 200. The researchers stated that it is difficult to exactly estimate the number of principal investigators in every sub-domain in neuroscience research in India given the multidisciplinary nature of the domain. Researchers estimate about 15 to 30 computational neuroscience principal investigators. To provide a comparison of where India stands in terms of number of researchers, the Society for Neuroscience a leading global association of researchers has about 36,000 members who are spread across 95 countries[8]. Some of the researchers in our study estimated that there are about 30,000 researchers in neuroscience in the USA. About 500 principal investigators are part of the Human Brain Project funded by the European Union[9]. A couple of researchers in our study also pointed to the fact that Zurich area in Switzerland alone is home to about 125 principal investigators in neuroscience.

Many of the national institutes of importance including Indian Institute of Science (IISc), Indian Institutes of Technology (IITs), NIMHANS, etc.; research centers like National Centre for Biological Sciences (NCBS), Institute for Stem Cell Biology and Regenerative Medicine (inStem), National Brain Research Centre (NBRC), etc.; and universities like University of Hyderabad, University of Allahabad, etc. have a research program in neuroscience. However, there are only a few master's programs in neuroscience (cognitive sciences) in India. Centre of Behavioral and Cognitive Sciences (CBCS), University of Allahabad; Centre for Neural & Cognitive Sciences, University of Hyderabad; Centre for Cognitive Science, IIT-Gandhinagar; School of Cognitive Science, Jadavpur University and Indian Institute of Speech and Hearing, Mysore offer master's programs. IIT Kanpur started a master's program in the fall of 2018. According to the portal Master'sportal.com10, there are about 53 neuroscience master's programs in the USA, 69 in the UK, and 21 in Germany.

2.3. Focus of research in India

Our study reveals that Indian researchers are inspired to find answers to some of the challenging problems in neuroscience.

- Modeling sensory (vision, speech, smell, etc.) and multisensory perception in humans
- Comprehending human abilities like attention, learning, causality, decision making, language, etc.
- Modeling how the brain works at multiple levels; cellular, network (of cells), etc.
- Brain inspired computational modeling techniques
- Brain inspired hardware architecture
- Developing alternative and better techniques to study the brain

7 http://neuroscienceacademy.org.in/about.php
8 https://www.sfn.org/About/Mission-and-Strategic-Plan
9 https://www.humanbrainproject.eu/en/about/overview/
10 https://www.master'sportal.com/search/#q=ci-82|di-226|lv-master,preparation|tc-EUR&start=0&order=relevance

The inspiration translates into focused research projects. Researchers in India are involved in different interesting projects covering different aspects of cognitive neuroscience, systems neuroscience, and computational neuroscience. A sample of these research projects that provide a flavor of the breadth of research include

Modeling sensory and multisensory perception	• Modeling multisensory perception like vision and speech • Modeling how the brain makes sense of properties of images like symmetry
Comprehending human abilities like attention, learning, causality, decision making, language, etc.	• Understanding adult language learning • Understanding social cognition • Understanding how attention and emotion interact • Identifying links between multilingualism, ageing, and dementia • Identifying screening tests for dyslexia in Indian languages • Studying the role of music in alleviating mood disorders • Connecting emotional state, brain state, and music
Modeling how the brain works at multiple levels; cellular, network (of cells) level, etc.	• Mapping molecular and electrical computation in cells. • Modeling networks of olfactory receptor neurons • Modeling the basal ganglia (part of the brain responsible for motor and cognitive functions) • Modeling the hippocampus (part of the brain responsible for memoryconsolidation) • Modeling networks of grid cells and place cells (types of neurons that help mammals navigate) • Studying the role of different brain regions like hippocampus, entrohinal cortex (part of the brain that acts as an interface node between other parts of the brain for memory and navigation) of rats when they are moving in space to understand their roles in navigation • Modeling neural signal and information processing • Identifying early onset of Alzheimer's disease by observing changes in synaptic transitions • Identifying how functionally specialized are different regions of the brain • Using optogenetics to monitor and stimulate the brain using light and watch brain activity during learning • REM Sleep

Brain inspired hardware architecture	- Designing systems that power specific networks based on task like brain - Designing a AI chip inspired by brain - Developing brain inspired computer architectures that minimize power consumption
Develop alternative and better techniques to study the brain	- Improving effectiveness and efficiency to process brain imaging data from functional Magnetic Resonance Imaging (fMRI) - Applying machine learning methods to identify resting state characteristics from MRI images of healthy and diseased brains - Improving the analysis of diffused Electroencephalography (EEG) signals using signal processing and biophysical modeling - Integrating data from different methods like EEG, MRI etc. - Improving spatial resolution of Near-infrared spectroscopy (NIRS)
Brain inspired computational modeling techniques	- Developing a simulator capable of molecular to network simulation - Developing new models in reinforcement learning - Studying the difference between how the brain works and how deep neural networks are different while processing symmetry in images - Developing efficient algorithms for deep learning and ML using cerebellum (part of brain responsible for coordination, precision, and accurate timing, and fine-tunes motor activity) models

Most researchers in India work with human subjects, and typically obtain brain data using non-invasive means like fMRI, MRI, and EEG. Some researchers work with other mammals especially rats and mice. These animals are typically implanted with electrodes implanted in their brains to obtain data. There is at least one Indian researcher whose subjects are monkeys implanted with electrodes in their brains to obtain data.

A couple of other facets of brain research emerged from our study. One, neuroscience is inherently multidisciplinary. Two, Indian neuroscience researchers often required funding support from organizations other than the universities or research institutions they are affiliated to.

2.4. Inherently multidisciplinary

One of the standout learning from our study is that almost all the researchers we spoke to stressed on the multidisciplinary nature of neuroscience. This implies that neuroscience is best suited to universities that have many of these disciplines. For example, we have seen neuroscience researchers housed in computer science, biomedical engineering, and even in linguistics departments in universities where there is no department for neuroscience. Focused neuroscience research centers seem to provide a better context to accommodate neuroscience researchers with different backgrounds.

We noticed a wide spectrum of disciplines that contributed to neuroscience research in India. These include

- Biological sciences: Biology, Zoology, Genetics
- Medicine: Psychiatry, Anatomy, Physiology, Neurology, Radiology
- Mathematical, Physical, and Chemical sciences: Mathematics, Physics, Biophysics, Chemistry, Biochemistry
- Engineering: Computer Science, Electronics, Biotechnology, Biomedical, Mechanical
- Other disciplines: Psychology, Linguistics, Anthropology, Sociology

World-wide, brain research is multi-disciplinary. Elsevier examined its Scopus database for trends in brain and neuroscience research from 2009 – 2013[11]. More than half (59.5%) of the 1.73 million active brain and neuroscience researchers were classified as multidisciplinary. Researchers published most often in the areas of medicine, biochemistry, and genetics and molecular biology, but the fields of engineering and computer science were also included among the top 20 disciplines in which active brain and neuroscience researchers published.

While the multidisciplinary nature of neuroscience makes it so much more interesting, it comes with its own set of challenges in India. The first challenge of neuroscience being multidisciplinary is that there are very few master's programs in neuroscience in India. One of the reasons for this low number is that there are only a few standalone departments to house and own such a degree. The second challenge is also related to the first. Neurosciences master's and PhDs have limited options in India since there are only a handful of universities and research institutes with a standalone neuroscience department.

The third challenge is to do with the structure of medical higher education in India. Medical universities are always almost independent of science and technology universities in India. This implies neuroscience researchers have to collaborate with clinicians from outside their university setup. Since clinicians are in high demand in India, it becomes difficult for many of them to devote adequate time for research. Another related observation that came up in our study is a view the medical higher education in India does not have a level of research focus that is present elsewhere in the world.

2.5. Funding for research

Public sources reveal the following.

- Department of Biotechnology (DBT), Government of India continues to fund the autonomous institution NBRC focused on brain research, and Institute for Stem Cell Biology and Regenerative Medicine (InStem) whose focus includes translational neuroscience[12]. In addition, DBT also funds research in neuroscience in Indian universities and research institutions. In 2017-18, DBT had a task force on neuroscience with a mandate to support research projects having disease centered approach.

11 https://www.elsevier.com/research-intelligence/research-initiatives/brain-science-report-2014
12 DBT Annual Report 2017-18

- DST and Ministry of Human Resources Development (MHRD) of Government of India also fund research and education in neuroscience in Indian universities and research institutions. DST has a focused Cognitive Science Research Initiative to fund neuroscience research[13].
- 17% of research funding by The Wellcome Trust DBT India Alliance is in neuroscience[14]. As a domain neuroscience is second only to cell and development biology that received 18% of funding from The Wellcome Trust DBT India Alliance. The total scientific costs for The Wellcome Trust DBT India Alliance in FY 2016 were INR 830 million[15].
- Pratiksha Trust will grant a sum of INR 2.25 billion over a period of 10 years towards the establishment and functioning of the Centre for Brain Research in IISc. The Pratiksha Trust has also provided INR 300 million to IIT Madras to fund three chairs in the Center for Computational Brain Research.
- Tata Trusts have provided a grant of INR 750 million to IISc to fund neuroscience research. This grant is also funding the setting-up of a fMRI facility in IISc

Setting up world-class lab infrastructure in neuroscience is expensive. Based on our discussions with researchers, we were able to assess the cost of setting up some of the lab infrastructure for neuroscience research. For example, buying an fMRI scanner system costs about INR 170 million to INR 200 million. The annual running cost is about INR 3 million to INR 4 million. Converting an existing MRI system into fMRI system costs about INR 10 million. Setting up high performance computing facilities required for neuroscience modeling can cost anywhere upwards of INR 5 million just for the computing equipment.

Among the big global announcements for neuroscience related research was the BRAIN initiative in the USA. Announced in 2013, it had an initial budget of USD 110 million (about INR 7.7 billion)[16]. The BRAIN initiative has received another USD 340 million (about INR 23.8 billion) since 2013.

So far we have discussed the input side of research. It is also equally important to understand how researchers measure the impact or output of research.

2.6. Measuring the impact of research

More than half the researchers we spoke to as part of the study mentioned that good quality research publications and subsequent citations is the most important measure of impact of research. The next important impact is the ability to attract and place doctoral students. Filing for patents did not feature as an important measure of impact; only a couple of researchers mentioned that they may explore filing patents at a later point in time. This is possibly to do with the basic research focus in the universities and research institutions. While patents are not always essential, it may be important to assess the impact how filing patent or not will impact translating the research into applications in neuroscience and computational neuroscience.

13 http://dst.gov.in/cognitive-science-research-initiative-csri
14 https://www.indiaalliance.org/funded-areas
15 https://www.indiaalliance.org/uploads/files/Report2015-17.pdf
16 http://www.braininitiative.org/milestones/

Some of the interesting perspectives that emerged as measures of impact include how research results have moved the discipline forward, and whether the results are replicable. There is a concern that an increased focus on publications may push researchers to game the process with sub-par results. There is a view among researchers that more importance should be given to quality of results, and if other researchers are using the results, models/protocols developed. International peer recognition in terms of being invited for invited talks, and recognition by international professional bodies like the Society for Neuroscience and similar organizations is also considered important for principal researchers. Last but not the least, a few researchers also mentioned the need to measure impact in terms of the translation of research into practical applications that benefit India and the world. A subset of this is for the research to be used by clinical practitioners and have a positive impact on patients.

While India is nurturing a world class research capability in neuroscience and computational neuroscience, it is imperative to understand and adopt relevant best practices from across the world to accelerate building this capability.

3. LEARNING FROM OTHER COUNTRIES AND RESEARCH COLLABORATIONS

In this section we shall highlight some of the brain research initiatives in other countries. The multidisciplinary nature of brain research naturally fosters research collaborations. Indian researchers are collaborating among themselves, and also with the best international researchers. The USA had its "decade of the brain" between 1990 and 1999. Interestingly, USA's "decade of the brain" is one of the inspirations for India to establish NBRC in 1998.

3.1. Brain research initiatives in other countries

G-Science Academies Statement 2016

In April 2016, the science academies of the G7 nations as well as seven additional academies including the Indian National Science Academy proposed a four-pronged call for action to cultivate global brain resources[17]

- Support fundamental research with international collaboration
- Establish global programs for the diagnosis, prevention and treatment of brain disorders
- Promote theoretical modeling of the brain and the development of brain-based artificial intelligence, and
- Integrate neuroscience with the social and behavioral sciences to improve education and life management as essential components of a brain-aware society

Global Brain Workshop 2016

The workshop identified three grand challenges for Global Brain Sciences, spanning anatomy, physiology, and medicine[18]

- Challenge 1: What makes our brains unique?
  - Construct comprehensive multi-scale maps of the ABCDE's (anatomy, biochemistry, connectivity, development, and gene expression) of multiple brains from multiple species using multiple cognitive and mental health disease models
- Challenge 2: How does the brain solve complex computational problems?
  - Measure, manipulate, and model neural activity simultaneously across many spatiotemporal resolutions and scales—including wearables, embedded sensors, and actuators—while animals are exhibiting complex ecological behaviours in naturalistic environments
- Challenge 3: How can we augment clinical decision-making to prevent disease and restore brain function?
  - Collecting, organizing and analyzing human and non-human anatomical and functional data. The distributed and multimodal nature of these datasets further motivate the need for an all-purpose computational platform, upon which models of disease can be developed, deployed, tested, and refined

Country-level Brain Research Initiatives

"Worldwide initiatives to advance brain research", an article authored by the heads of the nationwide

17 G-Science Academies Statement 2016
18 http://brainx.io/

neuroscience initiatives in China, Europe, Israel, Japan, and USA was published in Nature in 2016[19] This provides a strategy overview of the national level brain research initiatives in these countries. It is interesting to note the commonality, and the unique country-context motivated differences in these strategies.

A summary of the key brain research initiatives in these countries is provided below[20].

China

- The China Brain Project is expected to started in 2016.
- China's strategy is referred to as 'one body, two wings' framework. The central body of the initiative is to focus on the study of the neural basis of cognitive functions, with two wings addressing the translational aspects of neuroscience.
- The first translational aspect is to improve and develop early diagnosis and therapeutic interventions for major brain disorders. The second translational aspect is to develop brain–machine intelligence technologies including brain–machine interfaces, and brain-inspired computing methods and devices.

Europe

- The European Union's Human Brain Project (HBP) started in 2013.
- The emphasis of the HBP was on infrastructure development, simulations and modeling of the brains of mice and humans, based on a detailed neurobiological knowledge of the different parts of the brain.
- HBP has worked towards developing six different platforms for neuro-informatics, simulation, high performance computing, medical informatics, neuromorphic engineering and robotics.

Israel

- Israel Brain Technologies (IBT) started in 2011.
- Israel's recent strategy seems to focus on translation.
- IBT's mission is to accelerate brain-related innovation and commercialization leveraging the strengths of Israel's academic and clinical excellence in neuroscience combined with its preeminent position in entrepreneurship and technological innovation. The impact focus seems to be in growing the number and funding of Israeli brain technology projects and companies.

Japan

- Japan's Brain Mapping by Integrated Neuro-technologies for Disease Studies (Brain/MINDS) program started in 2014.
- A key goal of Brain/MINDS is mapping the brain of a marmoset which represents an important step toward gaining a better understanding of the human brain.

19 https://www.nature.com/articles/nn4371 (behind a pay wall)
20 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6047900/pdf/nihms978256.pdf

- The initiative generated a database for a marmoset whole-brain in situ hybridization atlas of over 400 genes. It has also produced an array of new tools and techniques for visualizing brain tissue and activity.

USA

- BRAIN initiative (Brain Research through Advancing Innovative Neurotechnologies) started in 2013.
- The objective is to construct a dynamic picture of brain function that integrates neuronal and circuit activity over time and space.
- Some outcomes from the initiative include a tool that uses designer drugs to turn on and off selected neurons, photoacoustic imaging technique to interrogate neural activity, and Z-brain, an open-source anatomical atlas of the entire zebrafish brain.

- Allen Institute for Brain Science (AIBS) started in 2003.
- The AIBS seeks to understand the biological and biophysical properties of the cerebral cortex.
- Key outcomes have been the Allen Mouse Brain Atlas, a comprehensive, cellular-level atlas of gene expression in the adult laboratory mouse, Allen Cell Type Database of single neurons from mouse and the Allen Brain Observatory data sets of cellular-level activity of mice visual-cortex.

Brain Research Foundations and Incubators

In addition to the educational and research institutions, several brain-research related foundations and incubators have emerged world-wide.

- Brain & Behavior Research Foundation (New York, NY)
- Brainnovation, Israel
- Dana Foundation & Dana Alliance for Brain Initiatives
- iPEPS-ICM, bioincubator of enterprises Paris-Salpêtrière
- Kavli Foundation (Oxnard, CA)
- Pediatric Brain Foundation (Springfield, MO)
- Simons Foundation (New York, NY)
- The Brain Forum, Zurich
- WEF, Global Agenda Council on Brain Research
- World Neuroscience Innovation Forum, London

3.2. Comparison of research publications and citations across countries

We also analyzed the data from Scimago Journal and Country Rank (SJR) for the category "Neuroscience" over the period 2013 to 2017 and compared it to India[21]. Our analysis shows that

Rank	Country	Citable Documents	Citations	Citable Docs ratio Country:India	Citation ratio Country:India
1	United States	112993	1152136	19.3	35.7
2	China	33825	214570	5.8	6.7
3	United Kingdom	31358	350193	5.3	10.9
4	Germany	29922	304065	5.1	9.4
5	Canada	20026	190154	3.4	5.9
6	Italy	17000	164387	2.9	5.1
7	Japan	16121	113758	2.7	3.5
8	Australia	14879	141128	2.5	4.4
9	France	14758	146969	2.5	4.6
10	Netherlands	11890	134869	2.0	4.2
11	Spain	10236	99157	1.7	3.1
12	Brazil	8532	52405	1.5	1.6
13	South Korea	8517	51705	1.5	1.6
14	Switzerland	8380	96233	1.4	3.0
15	Sweden	6216	65644	1.1	2.0
16	India	5864	32256	1.0	1.0
17	Belgium	5296	56778	0.9	1.8
18	Israel	4369	41011	0.7	1.3
19	Denmark	4133	40471	0.7	1.3

Source: Scimago Journal and Country Rank data for years 2013-2017

- Over the five years, India ranked sixteenth in the world in terms of number of citable documents in 'Neuroscience', and ranked nineteenth in terms of citations
- Over the last few years, India produces around 2% of the annual world research papers in Neuroscience

21 https://www.scimagojr.com/countryrank.php?area=2800&order=itp&ord=desc

- The top subject categories of neuroscience research papers from India are neurology, cellular & molecular neuroscience, cognitive neuroscience and other miscellaneous areas
- USA leads the world in terms of research publications and citations by a big margin. USA as compared to India, produced 19 times the number of citable documents and they were cited 36 times more often

3.3. Research collaborations

About three fourths of the researchers we interviewed as part of the study had collaborations with researchers in universities and institutions other than their own. About half of researchers are collaborating with Indian researchers in other universities or research institutions. About two thirds of the researchers are collaborating with researchers outside India.

Neuroscience is multidisciplinary, and it is natural for researchers to collaborate other researchers with complementary skills that help to solve research problems. For example, researchers with a computer science or engineering background seek to collaborate with researchers with a biological sciences background and vice versa. The single most sought-after Indian collaborators seem to clinical experts. As stated earlier, medical schools are not co-located in Indian technology and science universities. About one third of Indian neuroscience researchers mentioned that they are collaborating with clinical experts in India. (Refer to Appendix 2)

A sample of projects among Indian researchers include those in

- NCBS and IISc to understand the building blocks of synapses
- IIT Madras and University of Hyderabad to build a model of basal ganglia
- IIT Mandi, IIIT Ropar, and PGIMER Chandigarh to develop a low cost low magnetic field MRI for Point of Care Testing and associated CAD system

Most Indian researchers maintain the umbilical cord with the university where they completed their stint as a graduate student, post-doctoral researcher, or visiting researcher. Researchers who hold a dual appointment including in an Indian university are helping Indian researchers build a strong collaboration with their parent universities and international professional networks. Some of the international universities or research institutions with which Indian researchers collaborate include (in alphabetical order) Carnegie Mellon University (USA), Haskins Laboratories affiliated to Yale University (USA), MIT (USA), Salk Institute (USA), The Blue Brain Project - EPFL (Switzerland), University of Edinburgh (UK), etc. The quality of the universities and research institutions that Indian researchers are collaborating signals the quality of neuroscience in India. Some Indian neuroscientists have received peer recognition in conferences of the Society for Neuroscience, and believe that it is recognition for the entire Indian neuroscience research which has come of age. There is also an increased pull from neuroscience researchers from other countries wanting to work with Indian researchers based on the quality of Indian research.

A sample of projects with international researchers include those in

- NCBS, NIMHANS, and University of Edinburgh (UK) for computer models for detecting autism

- NBRC and MIT (USA) to build models of rat's brain
- NBRC and Haskins Laboratories (USA) to understand functional cortical (the cortex region in the brain is responsible for memory, attention, perception, cognition, awareness, thought, language, and consciousness) circuits for speech and reading in multilingual populations
- IISER Pune and Salk Institute (USA) on cellular and sub-cellular plasticity in the brain
- IISc and Carnegie Mellon University (USA) for researching neuro–degenerative diseases that afflict the aging population
- IIT Madras and Western Sydney University on developing computational neuroscience models of the basal ganglia

3.4. Industry collaborations

About one fourth of the researchers we spoke to had active collaborations with industry, or had collaborated with industry in the past, or in preliminary discussions to collaborate. One of the main reasons for the relatively lesser number of industry collaborations is due to the fact that most of the brain research in India is basic in nature and the number of principal investigators is not as high as in other regions of the world. We believe that is will take some time before there is an increase in translational research which may trigger more industry collaborations.

Some of the active industry collaborations we gleaned from our discussions with the researchers were the following

- A global chip major is collaborating with IIT Madras on designing a neuroscience inspired chip
- An Indian IT services company is collaborating with IIT Madras and University of Hyderabad on a project to use a neuroscience computational model to identify treatment for stroke
- A consumer products multinational collaborated with University of Allahabad for a project to understand how attention influences perception attractiveness
- Continental's R&D subsidiary in India is collaborating with IIT Madras to develop a neuroscience inspired control systems for autonomous vehicles[22]
- NIMHANS is in discussions with an Indian medical devices company to build a machine for interventions for patients with tinnitus (a perception of noise or ringing in the ears when there is none).

Multinational technology companies having their R&D and engineering subsidiaries in India seem to be interested in collaborating with Indian computational and systems neuroscience researchers. These multinationals include GE Healthcare, Samsung Research India, Microsoft Research, and IBM India Research Labs. Based on the information collected as part of this study, none of these multinationals currently have an in-house research team in India focusing on computational or system neuroscience as on mid 2018.

22 https://auto.economictimes.indiatimes.com/news/industry/continental-iit-madras-join-hands-for-safe-mobility-solutions/64028956

It is interesting to note that the collaborations and potential collaborations cover the gamut of technology, medical devices, IT services, and even consumer product companies. And the collaboration covers both Indian companies and multinationals. The nature of current collaborations especially with industry leads us to an associated aspect of translating research into applications.

4. TRANSLATING RESEARCH INTO APPLICATIONS

In this section we will identify some of the application areas of neuroscience and computational research. We also identify how basic research in brain science can be translated into applications.

Despite of the rapid advances in neuroscience research, we do not yet have a comprehensive understanding of the functioning of the brain. Neuroscience research efforts will continue in that direction in the coming years. There is a significant enhancement in brain imaging and computational capabilities in recent years and these have resulted in interesting applications of brain research. Based on our interviews with researchers as part of this study, we have identified application areas in the following categories

- Healthcare & Wellness related
- Brain inspired computing systems
- Applications in other industries like automotive, education, consumer marketing, etc.

4.1. Healthcare & Wellness related

Some of the important sub-domains include

- Diagnosis of brain disorders and other diseases
- Medical devices and Brain-Machine Interfaces (BMI) or Brain-Computer Interfaces (BCI)
- Pharmaceutical

One of the key application areas is in the early diagnosis and therapy of brain disorders like Alzheimer's disease, dementia, Parkinson's disease, autism, dyslexia and brain strokes. Computational neuroscience can have an impact on clinical neuroscience. For example, prevalent techniques of neurostimulation like Deep Brain Stimulation, Transcranial Magnetic Stimulation are largely based on thumb rules. We are seeing some treatments being based on computational and quantitative model of the patient's brain, thus driving towards the path of personalized rehabilitation.

Improvements based on brain research to underlying technology to process images are helpful in diagnosis of certain types of cancer. Projects are underway to understand complicated disorders of the vision. For example, some people can read an eye chart, but can't differentiate between faces.

We are seeing a number of applications in the area of Brain-Machine Interfaces (BMI) or Brain-Computer Interfaces (BCI). For example, a BCI interface for someone who is speech challenged or prosthetics solutions for the differently-abled. There are also some experiments being done in the area of computational neuropharmacology - studying the action of a drug at a multi-scale model - from molecular level to patient behavior level.

4.2. Brain inspired computing systems

Some of the important sub-domains include

- Artificial Intelligence (AI) systems and neuromorphic chips
- Smart edge devices
- Virtual reality and gaming

There are a number of interesting applications of brain research in building computationally efficient AI and computing systems. One project is to learn from the low-power nature of computing in the brain, and push AI to the edge devices. Another project is to build hardware / processor for handling data driven, event driven AI system. There are applications in speech recognition, especially in-home automation devices. There are some projects involving virtual reality gadgets and skull caps to monitor a gamer's brain, and enhance the gaming experience.

4.3. Applications in other industries

Brain inspired computer systems can transform any industry - like automotive, education, consumer marketing and advertising, mass media, music industry, military, forensics and others. In one Autonomous Vehicle project, efforts are being made to improve the camera-based computer vision system of the car using algorithm based on brain models. In another project, neuromarketing techniques are being applied to understand how consumers make choices while buying.

We asked the researchers whether they had any startups based on their research being incubated currently or in the future. Less than one fourth of the researchers feel that a startup is likely within the next 2 years. About one fourth of the researchers mentioned that there may be a startup within the next 5 years. Over half of the researchers feel either it is too early to tell or have no focus towards creating a startup.

4.4. Important factors that influence translational research

The general principle is that not all basic research should or needs to focus on translational aspects. The researchers we spoke to as part of this study shared their perspectives on factors affecting translational research in India. As seen earlier, the number of brain researchers in India is orders of magnitude lesser than researchers in the US and Europe. This implies that India does not have a large enough basic research throughput to seed translational research yet.

Some researchers are inherently theory-oriented and some are inherently application-oriented. The most important factor that influences translation is that it requires a tango between both types of researchers. Almost all the researchers we spoke to believe that one cannot force a theory-oriented researcher to do applications or an application-oriented researcher to work on basic research. Another factor that influences translational research is the multidisciplinary nature of brain research. Researchers with a computer science background working on neuroscience need to understand the working of the brain. Establishing a common vocabulary among researchers from different backgrounds takes time and if not addressed properly can lead to inefficient research and translational outcomes.

Since medical universities are independent of technology and science universities in the Indian context, setting up collaboration between these two institutions is often arduous. In some cases, there is also a mismatch between the objectives of collaboration between academia and industry. For example, some researchers feel that often industry is only interested in outsourcing their current research as part of the collaboration. The translation goals need to be clear with realistic expectations from both the academia and industry. Last but not the least, there are institutional challenges with respect to incentive structures for translating basic research into applications.

The next section describes Indian researchers' perspectives on how neuroscience and AI/ML are connected

5. CONNECT WITH ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

5.1. A brief history of brain-inspired AI/ML

In 1955, some of the founders of AI including Marvin Minsky, John McCarthy, Claude Shannon, and Nathan Rocheste sent a proposal for the Dartmouth summer research project on AI[23]. They proposed a 2 month, 10 person study to "find how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved for humans, and improve themselves. We think that a significant advance can be made in one or more of these problems if a carefully selected group of scientists work on it together for a summer."

AI originally envisaged creating an entity that possessed human like intelligence. While related academic fields such as operations research, statistics, pattern recognition, information theory and control theory already existed, and were often inspired by human and animal intelligence, these fields were arguably focused on “low-level” signals and decisions. The ability of, say, a squirrel to perceive the three-dimensional structure of the forest it lives in, and to leap among its branches, was inspirational to these fields. “AI” was meant to focus on something different — the “high-level” or “cognitive” capability of humans to “reason” and to “think.”[24]

Thus, began the brain-inspired journey of AI. In the initial years, neuroscientists and AI scientists had similar backgrounds and were well connected. But by the 1980s, AI diverged from a neural-type system to a logic driven system, one that focused on big stores of heuristics and rules to make decisions - more databases than neuroscience.

Recently, we have had multiple AI/ML researchers highlight problems that are keeping them from creating human-like artificial general intelligence, such as data hungriness, lack of transparency, and limited capacity for transfer[25]. Some have recommended that AI/ML should look into human cognition and deeply study natural language understanding and commonsense reasoning, some have argued the need for new research into unsupervised learning and understanding how the brain works. There is a view that human-level AI cannot emerge from current statistical mode machine learning systems, and they should be equipped with causal reasoning tools[26]. Some researchers recommend creating a virtuous circle that advances both AI/ML and neuroscience and learning higher level concepts like memory and imagination from the brain[27]. AI/ML and neuroscience are coming closer again.

A brief snapshot of brain initiatives in global technology companies. These initiatives are primarily driven by researchers based outside India.

- Google
    - The Google Brain team works to advance the state of the art in AI as one part of the overall Google AI effort

23 A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence, www.aaai.org
24 Artificial Intelligence — The Revolution Hasn't Happened Yet, Prof. Michael I. Jordan, UC Berkeley
25 Deep Learning: A Critical Appraisal, Gary Marcus
26 Theoretical Impediments to Machine Learning With Seven Sparks from the Causal Revolution, Prof. Judea Pearl, University of California Los Angeles
27 Neuroscience-Inspired Artificial Intelligence, Hassabis, Demis et al., Neuron , Volume 95 Issue 2, 2017, pp. 45 - 258

- Google Search, speech recognition systems, Google Photos, Google Maps and Street View, Google Translate, Google Cloud's Machine Learning offerings, YouTube, Gmail, DeepMind's AlphaGo system make use of technology from the Google Brain team
- Google is building tools and developing infrastructure to analyze petabyte scale datasets generated by the BRAIN Initiative

- IBM
  - IBM Research (AI & Cognitive Computing) builds applications that enable humans to collaborate with powerful AI technologies to discover, analyze and tackle the world's greatest challenges
  - IBM Watson
  - IBM Cognitive Environments Lab
  - TrueNorth – Chip design inspired by the human brain
  - IBM's Cognitive Horizons Network is a consortium of the world's leading universities committed to working with IBM to fulfil the promise of cognitive computing

- Intel
  - Collaboration with the Princeton Neuroscience Institute aims to map the human mind in real time and develop the next generation of brain imaging analysis
  - Collaborating with marine researchers in the Parley for the Oceans initiative
  - Deep learning portfolio - Knights Mill and Lake Crest (Nervana) for training neural networks, Movidius vision processors
  - Neuromorphic chip, Loihi

5.2. AI/ML and neuroscience – Perspectives from Indian researchers

With respect to how much of current AI/ML is brain inspired, two divergent views emerge. One set of Indian neuroscience and computational neuroscience researchers feel that current AI/ML is indeed brain inspired. Another set of researchers feel that we currently knew so little about the full functioning of the brain, and so it would be a stretch to say that current AI/ML is brain inspired. However, there is a broad convergence among Indian researchers that in the future, neuroscience has a lot to offer and will inspire the future developments in AI/ML. Some of the areas where neuroscience is likely to inspire AI/ML in the future include learning from sparse information, generalizing learning and transferring learning across domains, architecting systems that are as power efficient, etc.

A few salient themes that emerged from our discussions with researchers on AI/ML and neuroscience include

- Current AI/ML has its roots in an older understanding of the brain
- AI/ML can learn from the higher-level cognitive abilities of the brain
- AI/ML can also learn from the workings of the brains of other smaller species
- Need new AI/ML specific computer architectures
- AI/ML can mimic brain when computing hardware is made of biomaterials

Current AI/ML has its roots in an older understanding of the brain: Neural networks in AI/ML are inspired by the brain. They adopted just two concepts from the brain - neuron and multiple layers. Neuroscience models developed in the late 1960s are still being used. However, AI/ML doesn't take into account the detailed models of the brain cells now available. In future, AI/ML models are likely to draw inspiration from even more detailed brain models based on molecular, sub-cellular, and multi-cell biology models.

AI/ML can learn from the higher level cognitive abilities of the brain: Deep learning AI/ML systems rely heavily on labeled data. In contrast, the human brain has the ability to learn from very little information. Unlike current AI/ML systems, the brain does not need to be pre-trained.

AI/ML algorithms work very well for specific areas. For example, some image processing AI/ML algorithms perform even better than the human brain in recognizing images. One interesting technique to improve the image processing algorithms is to feed the AI/ML system data of EEG signals of a human viewing & recognizing a picture. But that same image processing AI/ML algorithm cannot perform other functions well, like catching a ball or processing sounds instead of images like humans do well. At some point in the future, AI/ML systems may mimic multi-tasking like humans.

As stated earlier, researchers are studying the structure and activities of the place cell and grid cell networks. These two cells are types of neurons found in mammalian brains that help with navigation. In fact they are called the global positioning system (GPS) of the mammalian brain. The models of these networks in the brain can be used to develop deep reinforcement learning AI/ML systems with mammal-like navigation capabilities.

AI/ML systems can incorporate memory into their models. A new machine called the Neural Turing Machine was developed in the UK/USA[28], which makes use of a big external memory connected to a neural network, thus mimicking neuro-biological architectures present in the human brain. This has the potential to inspire AI/ML systems can also learn from the concept of imagination and can develop a predictive model of the world.

AI/ML can also learn from the workings of the brains of other smaller species: Researchers confess that they know very little about how the human brain works and hence to say that we draw inspiration from brain to AI/ML is a tall order. Just like airplanes do not mimic birds for flight, it is not necessary for AI/ML to work like the human brain. To develop a small drone or a micro air vehicle that goes to a disaster zone and takes pictures, researchers can draw inspiration to develop an AI/ML system to navigate a drone based on a dragonfly's brain. It's conceivable that we develop full brain models of smaller animals first.

28 Neural Turing Machines, Alex Graves et al.

AI/ML specific computer architectures: When fMRI image of the brain is taken when a human is performing an activity we will notice that certain areas of the brain are active and others aren't. This is an example of an asynchronous architecture with spatially distributed and variable energy consumption. Neurons in the brain communicate asynchronously through the spikes and information is encoded in the timing of the spikes.

An analysis of an artificial neural network that is executed on a Graphics Processing Unit (GPU) or multi-core platform shows that, power consumed is completely uniform; every part of the network consumes the same power on every input, regardless of what input is given to it. All digital computers have a "global talk" which consumes 30-40% of the power of a computer. Today's AI/ML systems do not care about timing i.e. when an image/ pixel gets presented to a neural network, every neuron computes and it passes its output synchronously to the next neuron or layer. Thus it consumes a lot of energy to do the processing.

There is an opportunity to learn from the architecture of the brain and develop new AI/ML specific computer architectures for improvements in processing speeds and energy consumed. The new computer architecture may be characterized as fine grained parallelism, of being data driven, and event driven in their manner of operating the neurons and where at any given time only 1% or so of these neurons are working.

This kind of model is not suited to existing hardware. Researchers will have to build a specific hardware or processor to suit this kind of computational pattern. It is not just newer hardware, but newer algorithms are also being developed using event based processing. In the case of speech synthesis and recognition, these newer algorithms use 10X less data for training.

AI/ML can mimic brain when computing hardware is made of biomaterials: Current AI/ML is based on Turing machine implementations using silicon based semiconductors. The brain's function is controlled by the rhythmicity of chemical processes or membrane voltages and synchronization-desynchronization among them. This makes researchers look at biomaterials to mimic brain functionality instead of relying on current and emerging silicon based architectures.

These are fundamental research problems for the future, and answers to these questions may change the nature of human life in the future. It is only appropriate that Indian brain research is nurtured to ensure that India has a place on the table in the next era of human evolution.

6. RECOMMENDATIONS

In the previous sections, we focused on the landscape of brain research in India. We also contextualized this landscape with the external perspective of what other countries are doing. In this section, we will present a few salient recommendations for strengthening the brain research ecosystem in India.
An interesting demand from researchers was to declare a "decade of the brain" initiative in India to accelerate the ramp up of brain research. India should take notice. Now is the time to rapidly move the needle in brain research.

6.1. Increase the number of neuroscience research students in India

Some of the researchers feel that India needs to ramp up the numbers of principal investigators in brain research, and simultaneously increase associated investments in lab infrastructure. According to them, this will result in master's and undergraduate teaching programs to build a pipeline of researchers. This is a typical policy in the USA where setting up infrastructure often generates demand. Other researchers spoke about cutting through the bureaucracy that accompanies funding and setting-up lab infrastructure.

Many researchers interviewed feel that India should quickly ramp-up the master's programs in neuroscience, and also explore starting undergraduate programs in neuroscience. The priority focus area according to researchers is to increase the number of master's programs in neuroscience. The researchers we spoke to emphasized that this needs to be addressed on a war footing. The MIT (USA) model of setting up a neuroscience discipline is seen as a model for India to ramp up neuroscience in its technology and science universities. The current effort to set up biology departments in the Indian technology universities like the IITs is seen as a good start. Coupled with the existing strong engineering and physical and mathematical sciences departments, the IITs are seen to have a good foundation for nurturing a neuroscience department. An independent department makes it easier from an ownership perspective to introduce a master's program in neuroscience.

The importance of undergraduate programs in neuroscience is to help students decide on their interest in the field early on and whether to pursue further education in neuroscience or not. Some of the researchers cautioned about an unbridled proliferation of substandard undergraduate programs. An analogy is made to the undergraduate program in biotechnology. About 5,000 undergraduates emerge from these programs with the quality of many of these programs being sub-par. The researchers believe that India should learn from this experience, and ensure strict quality controls for undergraduate programs in neuroscience.

There is a unanimous agreement among researchers to ensure that pyramid for neuroscience professionals is managed well and also take into account undergraduate, graduate, and doctoral candidates dropping off to other fields like computer science or taking up jobs in industry.

Intensive summer schools also are a preferred model to train master's students in other disciplines in neuroscience. For example, three short courses on computational neuroscience were organized in NCBS. The Bernstein Center (Germany) model of universities coming together has had huge spinoffs in increasing the size at the base of the neuroscience talent pyramid. SMARTSTART is a training program of the Bernstein Network that supports young researchers to complement their previous studies with concepts, theories and techniques of computational neuroscience. Some of the researchers also feel that there needs to be better coordination between the various neuroscience summer and winter schools to ensure a larger participation, and more importantly focus on talent building in neuroscience and computational neuroscience.

6.2. Develop a strong multi-disciplinary research ecosystem in India

About one third of the researchers we spoke to as part of this study emphasized on building a strong multidisciplinary ecosystem that is the bedrock of brain research. This also includes building the right incentive structures for interdisciplinary research. Becoming truly multidisciplinary in the Indian context may be easier said than done. This includes starting from designing a multidisciplinary undergraduate and master's curriculum. The career path of the multidisciplinary brain researchers needs to be managed carefully by treating neuroscience as an independent discipline. At present, there is often a grey area on the right lens to use for evaluating a neuroscientist affiliated to the biomedical/biotechnology or computer science department in a university in India. This includes comparing the quality of research and publications in neuroscience and making a comparison with similar ones in biotechnology or computer science.

As stated earlier, Indian neuroscience researchers feel a need to have institutional mechanisms to foster closer collaboration between universities, research institutions and medical universities. Some of the researchers suggested setting up specialized brain research institutions in existing universities which have established departments in biological sciences, physical and mathematical sciences, engineering, and medicine. This is instead of setting up greenfield research institutions in isolated locations.

Some of the researchers pointed that the Indian universities rarely have a strong technology and medical department apart from the Banaras Hindu University (BHU). This is very different from the university context in the USA or Europe.

There is also a need to rejuvenate some of the existing institutions and bring them under a larger ecosystem. A case in point is the Schizophrenia Research Institute (SCARF) which does interesting research but is not well connected to other universities or research institutions.

Some of the multidisciplinary research institutions that were mentioned by researchers as role models in neuroscience include Redwood Institute (USA), Salk Institute (USA), Allen Institute (USA), Gatsby (UK), and EPFL (Switzerland).

A common thread that many researchers focused on is the importance of investing in state of art equipment like fMRI and associated labs that are expensive. In the Indian context, it may be worthwhile to examine if we want to treat these investments as national facilities for use by researchers from across the country. Another example is investing in a common facility for high performance computing infrastructure that can be on a private cloud and used by computational neuroscience researchers from across India. SuMegha, CDAC's Scientific Cloud India's cloud framework that provides High Performance Computing (HPC) resources for scientists especially in Life sciences and Climate Modeling areas. One of the researchers spoke about utilizing this framework for performing tractography (3D modeling) of the brain. Another researcher indicated that their deep learning models run on partner cloud infrastructure which provides GPU farms. These shared investments in state-of-the-art equipment improve the return of assets and controls running costs which is important in an Indian context.

6.3. Adopt a consortium or network model

A consortium model to nucleate blue-sky projects has been successfully employed in initiatives like the Human Brain project (Europe) and The BRAIN initiative (USA). In Germany, the Bernstein Network Computational Neuroscience was established through a central funding initiative of the German Federal Ministry of Education and Research in 2004. The network comprises six centers for computational neuroscience in four regions and eleven collaborations in neuroscience space.

According to some researchers in our study, India can consider setting up a consortium on modeling the cellular level of the brain function involving academia and industry - especially the pharmaceutical industry.

While the researchers feel that there is a need to imbibe best practices from other countries to nurture brain research in India, some researchers cautioned that India should not blindly adopt these best practices or favor only a big-bang approach. They believe that research community should contextualize the best practices for India before adopting.

One suggestion is that Indian neuroscience can focus on understanding the whole system, with a focus on one domain (example: one particular disease) rather than trying to replicate the Western attempts to model each cell of the brain.

Initiatives like Centre for Cellular and Molecular Platforms (C-CAMP) from Department of Biotechnology, Govt. of India, are starting to address some of the challenges associated with research and translational-research. C-CAMP facilitates bioscience research and entrepreneurship by providing research, development, training and services in state-of-the-art technology platforms[29]. It has provided access to its technology platforms to over 250 institutions in India, supported over 100 publications, has directly funded, incubated and mentored over 100 start-ups over the last few years. C-CAMP has obtained 'scale-up support' under the NITI Aayog's Atal Innovation Mission. Researchers in our study affirmed that C-CAMP should continue to strengthen its role as a trusted intermediary for both researchers and industry.

29 http://www.ccamp.res.in/about

Bangalore Life Science Cluster (BLiSc) is an innovative institutional model for cutting-edge scientific research. The cluster comprises three major institutes: National Centre for Biological Sciences (NCBS); Institute for Stem Cell Biology and Regenerative Medicine (inStem) and Centre for Cellular and Molecular Platforms (C-CAMP).

6.4. Collaborate on global initiatives & platforms for sharing data

Associated with the aspect of global research collaboration is the need for India to explore how data and code can be curated and shared. There is a global effort to make databases about the brain more usable and accessible for neuroscientists worldwide. Such efforts would be of great benefit to neuroscience, just as the availability of public genomic and protein structure databases have transformed genetics and biochemistry. Researchers in our study feel the need to promote use of standards from bodies like the International Neuroinformatics Coordination Facility (INCF) in India[30].

Other global data initiatives include:

- Existing public datasets include the Allen Brain Atlas, the Mouse Connectome Project, the Open Connectome Project, the CRCNS data sharing project, ModelDB, and the Human Connectome Project
- The NIH Big Data to Knowledge (BD2K) Initiative offers opportunities to neuroscientists to develop new standards and approaches[31]
- Neurodata Without Borders and its pilot project on data related to Neurophysiology[32]
- The Neuro Cloud Consortium has proposed a global data platform for leveraging cloud-computing technologies to enable large-scale neurodata storing, exploring, analyzing, and modelling[33]

Another important aspect that India needs to learn from other countries is to integrate ethics and neuroscience. The study of mental health is often considered as a blend of neuroscience and social science. As neuroscience models become more commonplace in AI/ML, care must also be taken to ensure that these models are devoid of biases and prejudices.

30 https://www.incf.org/network/nodes/india
31 https://datascience.nih.gov/bd2k/about
32 http://www.nwb.org/
33 http://dx.doi.org/10.1016/j.neuron.2016.10.033

Appendix: List of researchers interviewed for this study

We thank the researchers who graciously gave us time to understand different aspects of brain research in India.

1. Ahmed Moustafa, *Western Sydney University*
2. Anand Raghunathan, *IIT Madras, Purdue University*
3. Arpan Banerjee, *NRBC*
4. Aravind Kumar, *NIMHANS*
5. B. Ravindran, *IIT Madras*
6. Bapi Raju, *University of Hyderabad*
7. Birendra Mallick, *JNU*
8. Collins Assisi, *IISER Pune*
9. Dipanjan Ray, *NBRC*
10. Hema Murthy, *IIT Madras*
11. Krishna Prasad Miyapuram, *IIT Gandhinagar*
12. Kamal Kumar Choudhry, *IIT Ropar*
13. Kaushik Majumdar, *ISI Bangalore*
14. Nandini Singh, *NBRC*
15. Narayanan Srinivasan, *CBCS University of Allahabad*
16. S. P. Arun, *IISc*
17. Sachin Deshmukh, *IISc*
18. Shahid Jameel, *Wellcome-DBT Alliance*
19. Shantala Hegde, *NIMHANS*
20. Shubhajit Roy Chowdhury, *IIT Mandi*
21. Shyam Diwakar, *Amrita University*
22. Sridharan Devarajan, *IISc*
23. Srikanth Ramaswamy, *EPFL*
24. Srinivasa Chakravarthy, *IIT Madras*
25. Sriram Ganapathy, *IISc*
26. Suhita Nadkarni, *IISER Pune*
27. Supratim Ray, *IISc*
28. Tapan Kumar Gandhi, *IIT Delhi*
29. Upinder Bhalla, *NCBS*
30. Vasant Honavar, *IISc, Penn State*
31. Vinoo Alluri, *IIIT Hyderabad*

Appendix 2: Illustrative list of researcher-researcher collaboration

The following is an illustrative list of research collaborations between researchers from Indian and other Indian / foreign universities as mentioned by participants in our study (in alphabetical order).

1. Amrita University and University of Pavia (Italy) / Yale School of Medicine (USA)
2. Centre of Behavioural and Cognitive Sciences (CBCS), University of Allahabad and IIT Kanpur
3. EPFL (Switzerland) and IIT Madras
4. IIIT Hyderabad and Aarhus University (Denmark)
5. IISc and Carnegie Mellon University (USA)
6. IISc and Donders Institute (Netherlands)
7. IISc and École Normale Supérieure (Paris)
8. IISc and Penn State University (USA)
9. IISER Pune and Salk Institute (USA)
10. IISER Pune and University of California, San Diego (USA)
11. IIT Delhi and MIT (USA)
12. IIT Madras and MIT (USA)
13. IIT Madras and Purdue University (USA)
14. IIT Madras and University of Birmingham (UK)
15. IIT Madras and University of Western Sydney University
16. IIT Mandi and IIT Ropad, and Postgraduate Institute of Medical Education and Research (PGIMER) Chandigarh
17. IIT Ropar and University of Zurich (Switzerland)
18. Indian Statistical Institute (ISI) Bangalore Centre and University of Bonn (Germany)
19. JNU School of Life Sciences and All India Institute of Medical Sciences (AIIMS)
20. National Brain Research Centre (NBRC), Manesar and Institute of Plasma Research (India)
21. National Brain Research Centre (NBRC), Manesar and MIT (USA)
22. National Brain Research Centre (NBRC), Manesar and National Institute of Mental Health & Neuro Sciences (NIMHANS)
23. National Centre for Biological Sciences (NCBS), NIMHANS and University of Edinburgh (UK)
24. National Institute of Mental Health & Neuro Sciences (NIMHANS) and International Laboratory for BRAin, Music and Sound Research (BRAMS), Montreal (Canada)
25. National Institute of Mental Health & Neuro Sciences (NIMHANS) and Vivekananda Institute of Yoga
26. University of Hyderabad and INRIA (France)

About itihaasa Research and Digital

itihaasa Research and Digital (www.itihaasa.com) is a non-profit Section 8 company that aims to understand and chronicle the history and evolution of technologies and businesses in India. Kris Gopalakrishnan, co-founder Infosys, is the founder and Chairman of itihaasa Research and Digital.

Our flagship project is itihaasa history of Indian IT, a first-of-its-kind free digital museum app that recounts the history of Indian IT since the 1950s. This app makes the incredible history of Indian IT accessible to an audience across the world and is available on App Store (iOS) and Play Store (Android). It is also available through a chatbot on our website. itihaasa history of Indian IT is featured in the IEEE Annals of the History of Computing.

You can reach out to **N. Dayasindhu, PhD** (dayasindhu@itihaasa.com) and **Krishnan Narayanan** (krishnan@itihihaasa.com) for any queries / feedback on the study.

itihaasa
Research and Digital