TRENDS IN NEUROTECHNOLOGY

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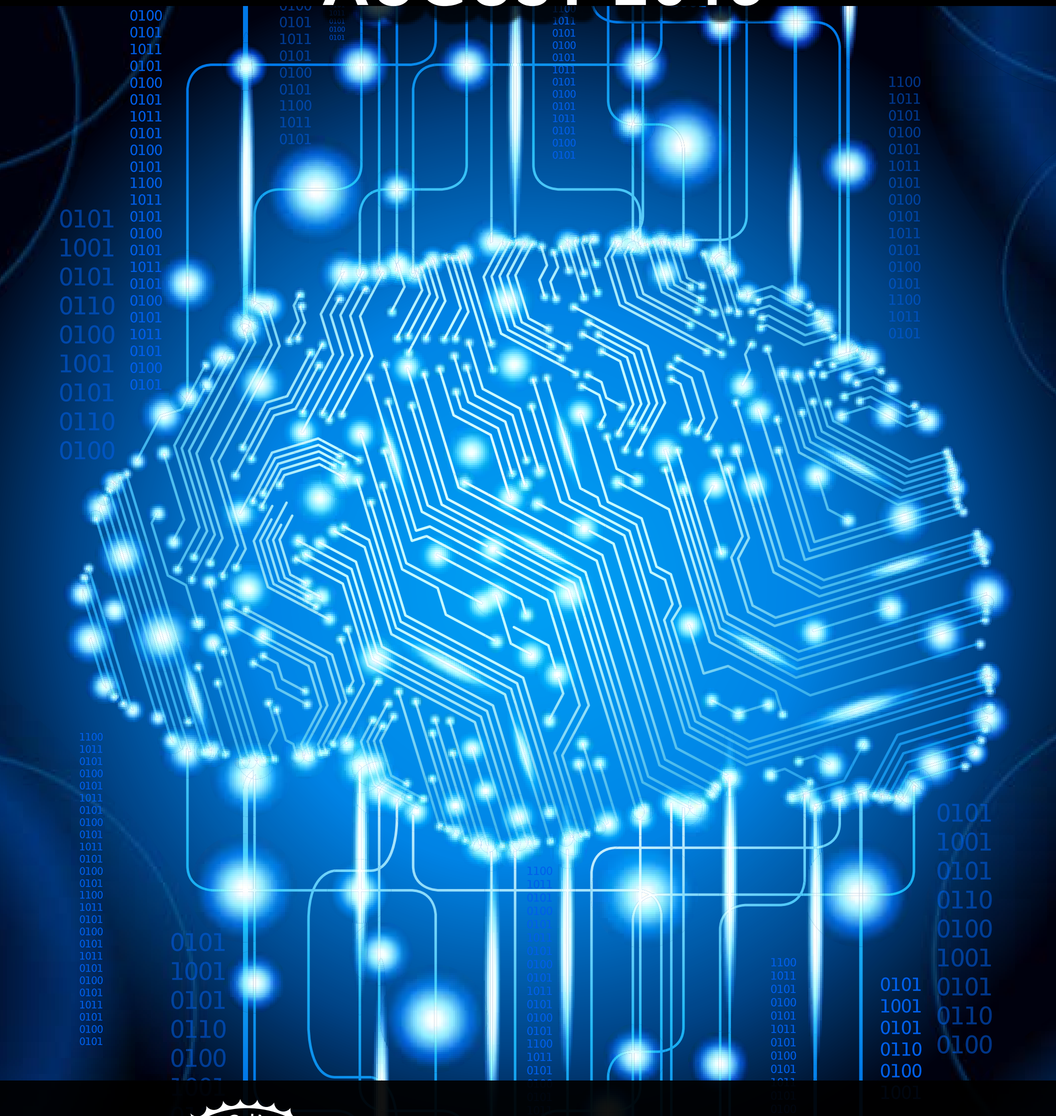

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The Center for Neurotechnology Studies provides neutral, in-depth analysis of matters at the intersection of neurotechnology and public policy. It provides a forum for reasoned consideration of these issues both by subject-area experts and by the public. The Center serves as authoritative counsel to government agencies pursuing neurotechnology, by providing expertise in the sciences, law, and policy through discussion on the implications of neurotechnology in academic, administrative, entrepreneurial, regulatory, legislative, and judicial enterprises. In turn, the Center is a highly sought partner by the research community for advice, partnership, and advocacy for the public and private funding of key neurotechnology research.

CNS

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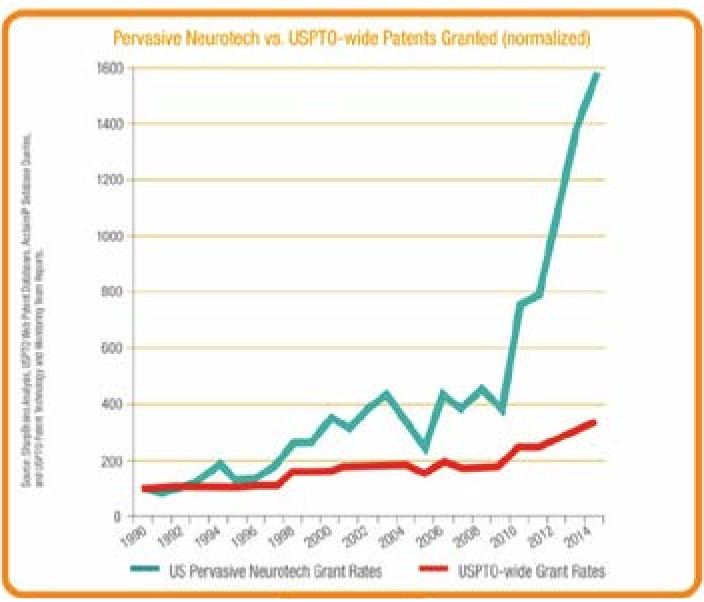
TRENDS IN NEUROTECHNOLOGY

Revolutions in neurotechnology will soon influence every aspect of human life. Neurotechnology can be used to further understand the natural processes of the brain, study and treat neurological disorders and injuries, and enhance neural capabilities, resulting in increased human intelligence and efficiency. Outside of the realm of health, it can be used in social contexts to improve overall quality of life. Neuroscience research has been on the rise for over 50 years, with publications in the field increasing at a steady rate (between 5-15% per year).[1] However, between 2012 and 2014, there was a 105% increase in the number of publications in neuroscience (calculations based on data from PubMed). This has also brought about a boom in neurotechnology innovation; patents doubled since 2010, and have quadrupled since the beginning of the millennium.[2,3] In 2010, 800 relevant patents were filed and by 2014, that number increased to over 1,600. There are currently over 8,000 active patents and over 1,500 pending applications.[4] The figure below depicts the growth of issued neurotechnology patents versus issued USPTO-wide patents.



Growth of Neurotech Patents Granted vs. All Patents Granted. Used with permission from SharpBrains.[4]

Medicine, defense, and law are just some of the contexts where we can apply recent advances in brain computer interfaces (BCI), cognitive load technology, and nerve stimulation. Neurotechnology incubators and accelerators have also provided a beneficial environment for startups hoping to effect change in the field. These incubators give startups initial access to seed funding, contribute mentorship, establish a curriculum, and introduce investors.[5]

It is acknowledged that advances in neurotechnology will benefit the field of medicine. Neuroscience has historically had a biomedical technology focus and new innovations are constantly being developed. For example, scientists recently discovered a noninvasive technology that uses ultrasound to clear away plaque in the brain that is responsible for Alzheimer's Disease.[6]

This report reviews recent technology trends in neuroscience. The information herein has been compiled through extensive literature review, seminars, and discussions with professionals at the forefront of the field. The report also analyzes the various impacts neurotechnology does, can, and will have on society, and identifies major funders of neurotechnology initiatives. Trends in increasing quality and quantity of neuroscience research allows us to create recommendations for the expansion of neurotechnology application. This information, assembled here, demonstrates the vast implications that neurotechnology has not only for particular fields such as medicine and defense, but also for society as a whole.

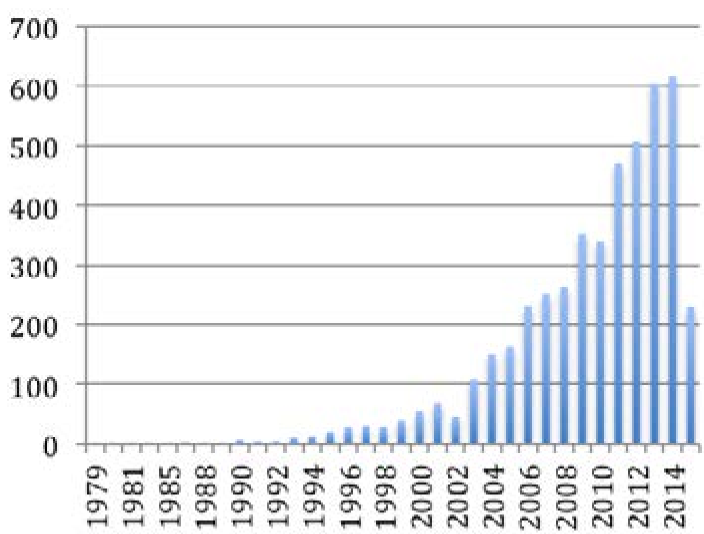
BRAIN-COMPUTER INTERFACES (BCIs)

BCIs have the potential to change how we perceive and control our environment, and have huge implications for the medical field, from enabling those who are paralyzed to perform everyday tasks to serving as a tool for diagnosis and assessment. Companies are developing applications for mobile devices that use software to read human faces and eyes. Almost 6.8 billion people in the world have cell phones, so gathering data on facial features would create an immense database of knowledge that could revolutionize the way technologies interact with people.[7] Such applications are currently used for attention and focus therapy. However, some developers are looking to advance the software to such an extent that eventually, applications will be able to look into the user's eyes, assess brain activity, and diagnose existing neurological condition such as Parkinson's Disease and Alzheimer's Disease. This software will be able to track the eyes' involuntary movements, which can indicate the presence of brain-related disorders through various detectable patterns.[8] If this development is facilitated, such technology could be clinically revolutionary.

Several studies and lab experiments have demonstrated that BCIs allow victims of paralysis to perform everyday activities through mere thought. Because most BCIs that have been studied require connection to an array of electronics, use in a home setting is currently far from feasible. However, new research groups have recently been able to create a BCI that has potential to work wirelessly.[9] A device, attached to the skull, is wired to several electrodes in the brain, and interprets and transmits data in the form of radio waves. These waves are transmitted to a receiver, where they become a signal to control an action. The data is transmitted faster than it has ever been before, but not up to par with the speed at which the human brain process and transmits data (through neuronal signals).

Scientists at Duke University have recently discovered that the brains of multiple animals can be connected to enhance the ability to perform specific tasks. Called a "shared brain-machine interface," this could have potential applications for patients with brain damage. Published research on both rats and monkeys suggests that the "collaboration" of multiple brains can produce superior performance than the work of a single brain.[10] This technology has vast implications for those who have neurological disabilities. In addition, this technology could be harnessed to enhance baseline intelligence, allowing multiple brains to cooperate over tasks and enhance performance. Research about BCIs has been funded by DARPA since the 1970s.[11] The U.S. military has also recently funded a $70 million project aimed at using BCIs to control emotions in the mentally ill. DARPA recently gave two large contracts to Massachusetts General Hospital and the University of California, San Francisco to create electrical brain implants for the treatment of psychiatric disorders.[12] Mental health is a major focal point for BCI research; over 2 billion people in the world have some type of mental health disorder. Applications are also developed to meet the need to treat victims of severe injuries, diagnose mental disorders, and for military and defense purposes. As seen in the figure below, research on BCIs is increasing rapidly – the market for BCIs is expected to expand to about $1.46 billion by 2020.[13]

Number of Publications on Brain Computer Interface Research



BCI Research Trends: Graph created using PubMed data organized by year.[14]

In addition to medical applications, BCIs have relevance in many fields. Hands-free device control user-state monitoring can be useful for automobile drivers, pilots, astronauts, and others engaged in focus-demanding tasks. The gaming industry is using BCIs to develop sounds, sights, and other characteristics in video games that mimic reality and give the player a more interactive experience. BCIs are being utilized for reaction and evaluation monitoring in fields such as marketing and ergonomics. BCIs are also being used to identify and monitor suspicious behavior and activity that can endanger public security. The automobile, advertising, and defense industries have invested in such technology and will likely increase investments as the potential of such applications grows.[15]

COGNITIVE LOAD TECHNOLOGIES

The human brain, though able to identify, process, and analyze with remarkable rapidity, does come under strain, especially in select circumstances. Cognitive load is the demand placed on working memory as people perform various tasks. An individual's cognitive load capacity impacts the ability to retain information, perform a series of tasks quickly or simultaneously, and communicate effectively.[16] Cognitive load can be high in several contexts. For example, customer service call center employees are expected to take back-to-back or even parallel calls while organizing and providing information, all while communicating effectively. The cognitive load from such a task is high, and those with a lower capacity for such load will perform less efficiently and potentially provide subpar service to customers. Companies have begun to use devices measuring cognitive load to help call centers hire optimum employees for dealing with high-demand, high-stress tasks to enable more efficient work coompletion.

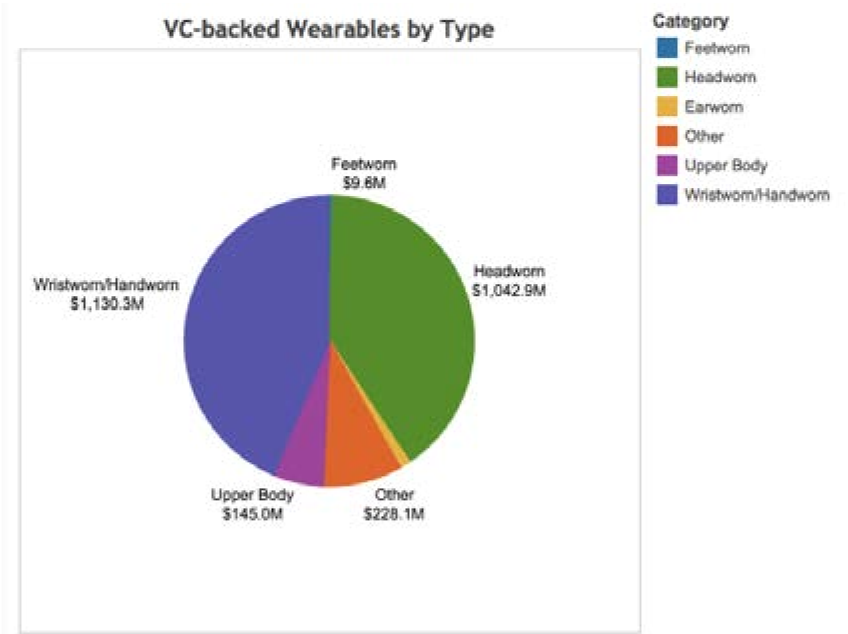
Cognitive load measurement is rising in prominence in the area of automotive research. Using heart rate, electrodermal activity measurements, and electroencephalography (EEG), cognitive load can be gauged to eventually combat circumstances such as distracted driving and driving under the influence. An annual conference, Automotive User Interfaces and Interactive Vehicular Applications, includes sessions on physiological sensors in user interfaces and on driver performance and behavior.[17] The Nielsen Company, the leading patent holder in pervasive neurotechnology, has also introduced a neurotechnology used for marketing to the automotive industry.[4,18] This technology can measure brainwaves and assess audience response to new vehicles and vehicular components, and gauge how customers would best be attracted to certain models over others.[19] This Nielsen Company innovation can be used for marketing in many industries and provides a scientific basis for the techniques used.

Similar strain can be observed on the battlefield, where soldiers must remain alert and detect and respond to imminent threats, oftentimes in a matter of seconds. Such situations can lead to fatigue and high false alarm rates. The detection tools normally given to soldiers include binoculars and portable radars, but these devices just do not offer an optimal visual range for target detection. The DARPA Cognitive Technology Threat Warning Systems (CT2WS) is a three-part system that involves a high resolution, high range video camera, cognitive visual processing algorithms that run on laptops, and an EEG that measures brainwaves to detect soldiers' subconscious detection of targets.[20] When all three devices were used together, soldiers were able to detect 91% of threats. There was also a very low false alarm rate. This reduction of cognitive load on the soldiers' brains affords them higher levels of concentration on their designated tasks, thereby potentially saving many lives.

Artificial Intelligence (AI) technology is a major avenue for cognitive load reduction. AI technology is any technology that can simulate abilities that previously only the human brain possessed. The interaction between such machines and users can enhance human ability to complete tasks efficiently while also reducing cognitive load.[21] Therefore, user productivity will raise baseline intelligence, allowing performance to surpass current optimal levels. Though not all AI technology directly interacts with the brain, the growth of the AI industry can fuel growth of the neurotechnology industry, as these technologies can be used together to increase efficiency and productivity. Venture Capital (VC) companies have been investing millions in AI, and reportedly over 170 startups work in this field. IBM is the leader in incorporating AI technology into industry. Through its IBM Watson Group, it has invested over $1 billion in the AI industry, with $100 million set aside for startups. Watson has been largely applied to healthcare and financial services, and works with both large companies and startups.[22]

WEARABLE TECHNOLOGIES

The sector of wearable neurotechnology, a branch under the umbrella of general wearable technologies, is growing rapidly as research increases the possibility of using wrist/hand/head-worn technologies to monitor and even control nervous system activity. Research at the Arizona State University has fueled a revolutionary new endeavor to create a lifestyle wearable that can optimize states of mind related to energy, calm, and focus. Over 70 startups have been formed based on ASU discoveries alone, and have attracted over $450 million in Venture Capital funding.[23] Such developments have been increasingly backed by VC funding. The following chart illustrates the distribution of VC funding for all types of wearables. Most wearable neurotechnology is wrist/hand/or head-worn and these technologies have attracted the most funding.



VC investment in wearable technology. Used with permission from CrunchBase. [24]

PAIN RELIEF

While pharmacological solutions for pain relief are effective, the side effects and addictive nature of certain drugs have encouraged the pursuit of alternative forms of treatment. Researchers and developers are investing resources in the investigation of pain relief modalities that affect the nervous system directly. By directly stimulating key receptors, neural interfaces potentially represent a more efficient method of alleviating the sensation of pain. Transcutaneous electrical nerve stimulation (TENS) is a non-pharmacological and noninvasive treatment method for chronic pain.[25] TENS-induced analgesia occurs through effects on both the central and peripheral systems. Application of TENS to afflicted areas activates opioid, serotonin, and muscarinic receptors in the spinal cord and brainstem and opioid receptors in the periphery. Though several studies have proved TENS to be effective, it is optimized when applied in particular intensities. These parameters are being tested and applied to developing stimulation technologies. Wearable technologies have been introduced to relieve chronic pain resulting from diabetic neuropathy, fibromyalgia, sciatica, and osteoarthritis, among other afflictions.[26,27] These devices can be useful for the military as well, to treat wound pain. Stimulation technologies may prove to be more effective than pharmaceuticals for the treatment of pain.

In addition to technology responsible for pain relief, there are devices that not only detect causes of chronic pain but also assess severity and monitor changes.[28, 29] For example, some devices measure sural nerve conduction velocity and response amplitude, which can quantitatively identify asymptomatic diabetic peripheral neuropathy (DPN), common in diabetic patients. Similar devices assess common neuropathies and provide quantitative information for nerve conduction studies. The advantages of such a technology include early detection that could reduce duration and cost of treatment.

SLEEP AND STRESS

With changing times and technology has come increasing demands on the nation's workforce, causing chronic stress levels to skyrocket. Chronic stress has many adverse health effects, including disruptions in sleep cycles and mental health effects. In recent times, development of universally usable technology to combat stress and sleep irregularity has surged, introducing several new devices to the market. There is a growing demand for technologies that can improve sleep quality, reduce stress, and maintain peak cognitive performance.

Now emerging on the market are medical-grade sleep aid masks that impact body clock and circadian rhythms through light therapy, which has been shown to help optimize sleep patterns.[30] These masks monitor biological signals such as EEG, EMG, pulse, eye movement, and body temperature, and wake the user at his or her lightest phase of sleep by creating lighting that simulates dawn. In addition, preliminary findings of a study examining the effects of light therapy on sleep and cognition after mild traumatic brain injury indicated that light therapy could be an effective way to regularize sleep cycles, reduce daytime sleepiness, and improve performance of tasks requiring attention and concentration.[31] While this technology can be a sleep aid that anyone can use, those affected by concussions and other mild brain injuries may find this type of device useful to treat and alleviate symptoms.

Other devices aim to reduce stress through meditation and focused activities in the form of headbands that monitor brain activity through seven sensors.[32] This headband is connected to a mobile application on which the user can track his or her brain activity. The application conducts the use through focus exercises, while the headband measures brainwaves that reflect the state of the user's mind. For example, the application can play sounds associated with how turbulent the headband perceives the user's brain activity (calm vs. excited). A similar device combines measurements of brainwaves, heart rate, and surrounding electromagnetic pollution to quantify the user's stress level.[33] The device and the application allow users to monitor how their stress oscillates, and can help users target which activities are helping and/or hurting their stress levels. These innovations can be used universally. They may be able to improve sleep and focus, and treat/prevent mental disorders.

Brain Wave Entrainment is an emerging technology that can be used to synchronize brainwave frequencies with a periodic stimulus to reach a desired brain-state. This stimulus can be in the form of light, sound, or vibration, for example. This technology can induce calm, relaxation, and sleep. In addition, it can enhance concentration while performing specific tasks, allowing for increased productivity. Brain Wave Entrainment leads to an almost instantaneous change in brain frequency and state, justifying its use as sleep/stress/focus aiding consumer technology. Research at the Washington University of Medicine in St. Louis has also shown that when people's brains are in a Delta brain wave state, production of beta amyloid plaque, which is a major cause of Alzheimer's Disease (AD), stops. Researchers are exploring the possibility of using this entrainment technology to help treat AD.[34] There are a fair number of startups focusing on this technology for general public use, and there is a growing demand for devices. This trend is in the same vein as companies that are marketing methods for improving attention, despite lacking a sufficient body of neuroscience research behind the technology or software.

IMAGING

Neuroimaging is used to study the brain both structurally and functionally, and advances in this area are trying to overcome the current limitations in the number of available techniques as well as the resolution of imaging. Researchers are not always able to effectively use imaging techniques while the subject is engaged in physical activity. New portable imaging technology may provide the foundation for more accurate neuroimaging during movement.[35] One device on the market uses the fNIRS (functional Near-Infrared Spectroscopy) imaging system that is wearable and measures activity in the prefrontal cortex. This imaging system measures changes in blood oxygenation and deoxygenation, called cerebral hemodynamics. Users can track, on a mobile application, levels of oxygenated and deoxygenated hemoglobin and which parts of the brain are activated. This device can be useful for field researchers, and may even be able to lead the way to developing portable versions of other neuroimaging formats.

Imaging is also being used to explore the potential to create "mind movies." Researchers at UC Berkeley have found a way to use imaging to read the electronic signals of a human brain and reconstruct the signals on a computer in the form of a movie.[36] This preliminary form of mind reading opens doors for use in the justice system and to explore the psyche of patients with mental disorders.

Neuroimaging has been the primary technology used to create structural and functional maps of the brain, which is a primary goal of the BRAIN Initiative. However, other technologies are emerging that could serve the same purpose. At an MIT lab, material scientists have created neural probes that can transmit and collect electricity while carrying light and can also pump drugs.[37] This is all done through ultrathin fibers that are implanted into the brain. Such probes can not only read electrical signals but also stimulate neurons to produce them. This could be a medium that enhances our knowledge of the corresponding structures and functions in the brain. In addition, this could have medical implications, as the capability of pumping drugs through the fibers to specific parts of the brain could revolutionize treatment for those affected by neurological disorders or brain trauma.

Another emerging technology that could prove to be more effective for brain mapping is injectable implant devices.[38] This technology will provide insights into how electrical impulses from particular networks of neurons relate to specific functions. It could also provide insights into the pathology of neurological disorders such as schizophrenia or Parkinson's Disease. These alternative options to neuroimaging, once put to wide use, could revolutionize the process of brain mapping, allowing researchers to understand structure-function relationships at a deeper level.

NEUROTECHNOLOGY CAPITAL

The White House's BRAIN Initiative, announced in 2013, allocated $200 million a year for brain-related research and brought about a surge in neurotechnology endeavors. As of 2013, 800 companies around the world were involved with neurotechnology. In the year 2000, there were 422 USPTO Patent Subclasses, while there were 899 in 2014.[4] This growth shows that neurotechnology has extended to more industries than ever before. Investment in neuroscience research has expanded significantly as well, with governments and private organizations investing billions of dollars annually. The global neurotechnology industry saw $160 billion in revenue, between pharmaceuticals, devices, and diagnostics. Of the three, neural pharmaceuticals had by far the largest revenue.[39] Compared to investment in neurotechnology in the medical field, investment for non-medical applications is relatively small, remaining in the hundreds of millions. However, neurotechnology applications can span several fields; all discoveries will have huge implications.

Of NIH's $30.2 billion budget, $100 million is allocated to the BRAIN Initiative. In addition, NIH is provided with an additional $30 million to pursue a program inspired by DARPA. In addition, the Opportunity, Growth, and Security Initiative proposed to allocate $970 million more to NIH, from which more money could be allocated to brain-related research and grants.[40] NIH announced that $46 million of its funds will go towards grants for research to produce tools and technologies relevant to the BRAIN Initiative.[41]

For FY15, of its $2.9 billion budget, DARPA plans to invest $80 million towards research contributing to the goals of the BRAIN Initiative. A major focus for this year remains BCIs, as well as projects attempting to decode the brain activity of higher-order mammals to provide a better idea of the neural networks in the human brain.[40] DARPA has invested close to $40 million for research on neurotechnology for memory disorders.

From its $7.3 billion budget, NSF plans to invest $20 million towards brain-related research. NSF is more focused on a cyberinfrastructure initiative that will advance high performance computing that will develop new systems with which to visualize and analyze data. This advance may effectively facilitate research in all fields, indirectly impacting progress in brain-related research.[40]

Global venture capital investment in neurotechnology in 2013 amounted to $1.44 billion.[39] Since 2000, promising neurotechnology startups have received over $19 billion from venture capital funds. Between 2013 and 2014, funding nearly tripled, going from $361.5 million to about $1 billion.

NEUROTECHNOLOGY TREND IMPACTS AND ADVANCES

As outlined in this report, neurotechnology is enabling incredible changes to our nation's capabilities in technology, security, individual achievement, communications, commerce, and education. One of the most important characteristics of neurotechnology is that its applications are not limited to cures for diseases and disorders. On the contrary, advances in neurotechnology will impact many different fields, including medicine, defense and intelligence agency operations, the justice system, advertising, business, communications, and even politics. Neurotechnology can help to cure mental disorders, understand human thought processes, improve imaging and BCI, and reduce cognitive load. Such technologies can enhance human intelligence, making people more efficient, alert, and effective. The existing success stories seen on the market today strongly suggest that investors in neurotechnology will reap enormous benefits. Neurotechnology will revolutionize the way in which society functions through the enhancement of human intelligence and physical abilities. As neurotechnology begins to reach into every aspect of our lives, the benefits to our health, education, and economy could be limitless.

Advances in neurotechnology are reaching new heights, where they are joining with and informing computing, artificial intelligence, biologics, and nanotechnology. The synergistic nature of these advances means that new paradigms and technologies for enhancing humans will develop at exponential rates. The way that we treat and understand the human brain will be transformed by big data analytics of large populations, nano-scale therapies, and improved neurotechnologies. These trends demonstrate the complex roles that the federal government, industry, and academic research can play in developing a successful neurotechnology field. While the President's BRAIN initiative represents a significant government investment in neurotechnology, it is a minuscule contribution when compared to the billions of dollars invested by venture capital funds and private researchers.

These developments will come about sooner than most people realize, and will revolutionize the way we receive, perceive, and project thoughts and memories. We will able to read people's thoughts and memories, and be able to apply this technology to patients of neurological disorders, prisoners, criminals, and witnesses. In the near future, it will be possible to create images using our thoughts and dreams, providing an entirely new means of communication. Neuroimaging technology can bring about the possibility of documenting and sharing dreams, ideas, and abstract concepts. People will not only be able to control machines with their minds but also share thoughts with each other. These applications seem surreal, but technology has progressed to a point that these capabilities will very soon be reality. Researchers and technology developers have already been able to achieve what many had not considered feasible just a decade ago. Increased investment in neurotechnology endeavors will make possible total achievement of the goals of the BRAIN Initiative, decrease the prevalence of mental disorders and physical disabilities, and allow for the continual improvement of the United States' social, political, and economic systems.

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TRENDS IN NEUROTECHNOLOGY

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