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Emerging neurotechnologies: Trends, relevance and prospects

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Abstract

Neurotechnologies are at the forefront of converging technologies because of their potential to restore and enhance normal brain function. Some dual-use neurotechnologies are used to assess the structure and function of the brain, others are interventional. These applications can diagnose and treat neurological conditions, and/or alter emotions, decision-making and productivity. Additionally, neurotechnologies may determine and define what it means to be human as we know it. Currently, an inventory of neurotechnological advancements is lacking, despite discussions of the current and future developments and the ensuing ethical issues. This paper aims to elucidate the range and pace of neurotechnologic innovation and their applications for future policy. Using the 'scanning' technique to assess the latest developments published on the internet, online databases were searched utilizing English key words for verified, authentic sources of data in the field of neurotechnology, yielding results from original scientific literature, media publications and reports. The most recent neurotechnological developments found were broadly categorized into - 1) Monitoring and Imaging; 2) Modeling and Reverse Engineering; 3) Brain-Machine Interfaces and Prosthetics/Orthotics; 4) Neuromics; and 5) Psychopharmacology. The impact of neurotechnologies is being increasingly felt - beyond medicine - in business, law, sports, arts and entertainment, national defense and even religion, and is laden with both promise and (potential) peril. This paper 1) attempts to establishe a 'baseline' against which to compare future advances in the field by providing depiction of current state-of-the-art neurotechnologies, and 2) raises ethical and policy questions that warrant further investigation.

Key words: neurotechnologies, neuroethics, scanning techniques, forecasting, technology convergence, policy implications

> *"…The union of human and machine, in which the knowledge and skills embedded in our brains will be combined with the vastly greater capacity, speed, and knowledge-sharing ability of our own creations. That merging is the essence of the Singularity, an era in which our intelligence will become increasingly non-biological and trillions of times more powerful than it is today—the dawning of a new civilization that will enable us to transcend our biological limitations and amplify our creativity.*
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> *In this new world, there will be no clear distinction between human and machine, real reality and virtual reality. We will be able to assume different bodies and take on a range of personae at will. In practical terms, human aging and illness will be reversed; pollution will be stopped; world hunger and poverty will be solved. Nanotechnology will make it possible to create virtually any physical product using inexpensive information processes and will ultimately turn even death into a soluble problem."*
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> *– Ray Kurzweil (1)*

Visions for the Future

The 'Singularity', anticipated to occur around 2045 (1), is but one of the many visions offered for our future. The current "Knowledge Era" driven by information technologies is proposed to give rise to the "Age of Consciousness" during 2020-30 (2), and creation of a "Health Advocate Avatar" by 2029 (3). Others have offered future visions to include a plateau, recurrent collapse and extinction of human civilizations as alternatives to post-humanity (4). These visions are typically accompanied by varying levels of acceptance about the pursuit and directionality of technology. Indeed, there is a perceptible divide- among scientists, technologists, ethicists, religious followers and lay public- about the reliance upon technology as a means to improve the human condition. Broadly, these perceptions and positions can be grouped into 'transhumanists' and 'bioconservatives' constituting the two poles of the new 'biopolitical' axis (5). This provides a novel paradigm of economic and cultural socio-politics. These divides manifest in the form of debates and movements, for example, about human identity and dignity, reproductive rights, life extension and human enhancement.

Converging Technologies

Technology has existed since before civilization in various forms (6). A major shift occurred when technology moved from a gross production mode to one based on or rooted in knowledge (6,7).

Technological Convergence is the term assigned to the inevitable, progressive and ever accelerating merging of information, biomedical and nanotechnologies (8-10). While each field or sector is undergoing progress in itself, the trend points to increasingly cross-sectoral developments that will elicit a greater impact (8). These interactions have grown to the point of being "the rule" rather than the exception. Information technology has been leading the technologic revolution thus far, but nanotechnology is considered to be the next wave that will irrevocably alter the overall millieu (9).

Information Technology (IT): Within the information technology sector, enhanced data processing and storage, increased voice and language processing, widespread wireless technology, integrated entertainment and communication systems, and e-work are envisioned over the next decade (3,8). Information technology was extensively utilized in the Human Genome Project (HGP), launched in 1990, that sequenced and mapped the large number of genes of Homo sapiens. Such a synergistic crossover of technologies is anticipated to continue.

Biomedical Technology (BT): Aided by information and nanotechnologies, further advances are expected in the realm of biotechnology (3,8). These include: computational chemistry for drug design; bioinformatics to process large amounts of biomedical data; instant and reliable screening and diagnostic tests; pharmacogenomics for personalized medicine; stem cell and genetic therapy; tissue engineering, and artificial limbs/organs. Taking genetic engineering one step further, there is momentum to create biological systems that do not occur naturally, as well as to re-engineer existing biological systems to perform novel tasks, contributing to the emerging field of *synthetic biology*.

Nanotechnology (NT): Current research aimed at nanomaterials can have the potential to create 3-dimensional structural self-assemblies that can be used as components in devices and systems of information technology. This changes dependence from microelectronics to nanoelectronics, and thus allows for molecular computing. Potential applications of these technologies include environmental surveillance monitors, enhanced batteries and biological sensors, targeted drug delivery and improved performance of medical implants and prosthetic devices (3,8).

Cognitive Sciences: A confluence of IT, nanotechnology and biology is occuring in cognitive science- a field comprising cognitive psychology, cultural anthropology, neuroscience and artificial intelligence (9). Cognitive science refers to psychological and physiological processes that underlie neural information processing, emotion, motivation, social influence and development. Aided by the aforementioned technologies, cognitive science and neurotechnologies are an important focus of the proposed, forthcoming Decade of the Mind.

Neurotechnologies and Neuroethics

Neurotechnologies (also called cognitive technologies) can be defined as a set of tools, methodologies and approaches to monitor, access, restore/treat, or augment/enhance and/or stimulate the nervous system. Neurotechnologies are an integral part of the progressive and accelerated convergence of knowledge and capabilities of bio-, nano- and information technologies and cognitive science, and include *de novo* technologies as well as existing technologies that are used in novel applications.

Neuroethics refers to both the neurological mechanisms of morality, and the ethical (legal, economic, and social) issues arising out of research and applications of the neurosciences and neurotechnologies (11). In this latter domain, the issues include safety, privacy, stigma, discrimination, and justice. In addition, since neurotechnologies alter brain function - and thus affect consciousness and mind - neuroethics also addresses novel and growing concerns of responsibility, moral regard, and human identity.

Objectives

According to the latest Neurotechnology Industry Report (12), in 2008 –

- Brain-related illnesses are the largest unmet medical market, affecting over two billion people worldwide

- Global neurotechnology industry revenues rose 9.0% to $144.5 billion
- Neuropharmaceutical sales recorded revenues of $121.6 billion and 9.3% annual growth
- Neurodevice sales recorded revenues of $6.1 billion and 18.6% annual growth
- Neurodiagnostic sales recorded revenues of $16.8 billion and 4% annual growth.

As staggering as these numbers may seem, the data do not capture the current breadth and depth of neurotechnological innovation. To appreciate the impact of converging technologies over the next few decades- and the ensuing ethical and policy issues, such convergence may generate- it becomes necessary to assess the state-of-the-art of neurotechnology. Several studies have discussed current and future developments relevant to a particular topic/area of interest, or group of technologies (13-23). However, an more complete inventory of neuroscientific findings and technological advancements is currently lacking, and definitions and categories are not entirely consistent among these studies.

Thus, the objective of the present study was to elucidate the range and pace of salient innovations in neurotechnology. We employed the well-established *scanning* method to conduct online searches for the latest developments published on the internet. We then categorized the data appropriately, and provided representative examples for each of the categories. We intend that this baseline will give scholars and policy-makers a sense of the directionality of neurotechnological advancement. Finally, we conclude the discussion with an outline of ethics and policy issues that beg further study.

Method

Emerging technologies are prone to both optimistic and pessimistic forecasts. Therefore, any forecasting needs to be based upon rational, explicit and rigorous scrutiny, preparation and analyses. This could involve various techniques, such as environment scanning, past and current trend analysis, polling, modeling and scenario building among others, to identify those fields that reveal indicators of progress, promise and problems (24).

Most predictions/projections of emerging technologies typically include – a) *year* of emergence of a particular technology, b) *probability* of such an estimate, c) the *market demand*, and d) the *country* where it originates (23,25). Unlike hypothesis testing, forecasting does not claim to eliminate uncertainty. However, it does provide for an estimated temporal window for a given technology to develop, and this is often adequate for policy makers to anticipate and respond, and affect the societal impact(s) of any new technology.

A first step is to realistically asses the current state-of-the field. *Environmental scanning* is a well-established technique that allows depiction of significant breakthroughs, as well as revealing areas with most and least activity within the field (23). In addition, scanning also facilitates identifying developments in seemingly unrelated fields that may have significantly impact upon the target technology of interest.

The paper utilizes this scanning technique, exploiting the databases of latest developments as published on the internet. Key words were entered into the Google web search engine as well as PubMed online database, and included generic terms (ex: neurotechnologies, reverse engineering and brain-machine interfaces) as well as more focused searches (ex: virtual reality, fMRI and exoskeletons). This yielded results from a range of sources including original scientific literature, media and company publications, reports and other articles. Data were traced to their original sources and verified for authenticity before being included in the results. Each selected data point was linked to its online source and date of publication, and was subsequently grouped into one of the five categories discussed in the proceeding section. Representative publications through this method are presented in Tables I-V. Of course, these citations do not represent or reflect all of the scientific and/or lay literature that is available to address each of the topical domains. Torward that end, a multiple resource (e.g.- Index Medicus; Scopus; EMBASE; etc.) polyglot (i.e., multi-lingual) search is recommended.

Results

Neurotechnologies have the capacity to fulfill both medical *needs*, and also the potential to realize non-medical *desires*. It is important to remember that needs and desires can vary significantly among individuals, within the same individual over time, and between particular groups and societies.

Neurotechnologies can be classified, for the purposes of clarity, into five major categories based upon the mode of action and/or function; these are:

1) Monitoring and Imaging,
2) Modeling and Reverse Engineering,
3) Brain-Machine Interfaces and Prosthetics/Orthotics,
4) Neuromics, and
5) Psychopharmacology.

For each category of neurotechnology, we provide a brief description, followed by scanning data of its current and potential future uses, to illustrate the range and pace of innovation(s). Each headline is followed by the source and date of publication (for supplemental source information, please refer to the Notes section of this manuscript). However, the discussion will refrain from 1) making forecasts, or projections; 2) analyzing the validity of the scientific theory, method and mechanism; 3) predicting likelihood of success; 4) analyzing timeframe and magnitude of impact; and 5) posing specific ethical arguments for or against any technology. In this way, this paper will serve more as a descriptive, informative survey of the numerous (and at times perhaps unsettling) possibilities enabled/afforded by current neurotechnology.

1) *Monitoring and Imaging* tools are non-invasive approaches that are primarily used in diagnostic or research settings to study brain anatomy, detect static or real time brain activity, and differentially localize activities to particular neuroanatomical regions (13-15). Examples of such technologies include positron emission tomography (PET), single photon emission computerized tomography (SPECT), functional magnetic resonance imaging (fMRI), and diffusion tensor imaging (DTI). Physiological monitoring technologies include magneto-and quantitative encephalography (MEG, QEEG). The EEG technologies measure electrical or magnetic fluctuations

Table I: Neurotechnologies- Monitoring and Imaging

- An fMRI study explains how the same neural code in the brain allows people to distinguish between different types of sounds, such as speech and music, or different images. [PhysOrg, 08/12/09] [i]
- fMRI studies indicate love activates the same system as the one with cocaine. [Esquire, 05/18/09] [ii]
- Using fMRI, psychologists have found that thought pattern used to recall the past and imagine the future is strikingly similar. [Science Daily, 07/01/07] [iii]
- Researchers find that fMRI may measure not only what the brain is doing, but what it is about to do. [Scientific American, 01/22/09] [iv]
- A PET scan, followed by fMRI, of asymptomatic patients has shown promise to predict onset of Alzheimer's disease (AD). [Neuron, 07/29/09] [v]
- Companies like No Lie MRI and Cephos *claim* to provide unbiased brain imaging methods for 'truth verification' with 90-93% accuracy. [Time, 07/20/09] [vi]
- fMRI study of men and women under stress showed how their brains differed in response to stressful situations. [Science Daily, 04/01/08] [vii]
- An EEG test is able to predict whether people in their 60's and 70's will develop dementia over the next 7 to 10 years with up to 95% accuracy. [Annals of the New York Academy of Sciences, 04/02/07] [viii]
- Amen Clinics is using single photon emission computed tomography (SPECT) brain imaging in making neuropsychiatric diagnoses and individualizing treatment plans (ex: ADHD in children). [ix]
- A neuroeconomic fMRI study provides a formal account of how we weigh our different experiences in guiding our future actions. [Nature Neuroscience, 08/05/07] [x]
- Neuromarketing study of media by Sands Research challenges instant analysis of 2009 Super Bowl XLIII ads. [Reuters, 02/24/09] [xi]
- fMRI study on meditation revealed significantly larger cerebral volumes and increased gray matter in meditators. [Science Daily, 05/13/09] [xii]
- fMRI scans provide further evidence that religion involves neurological regions vital for social intelligence. [Wired, 10/02/09] [xiii]

of neuronal activities; (these approaches record changes in localization of radioactive isotope-based binding or cerebral blood flow respectively, and both provide indirect measures of neural activity).

Despite extant limitations of this technology (14), the spatial and temporal resolution of monitoring and imaging technologies is expected to significantly improve over the coming years, accompanied by an exponential increase in computing power, and reductions in scanner size and costs. This affords the potential to conduct real-time scans- even molecular imaging- of moving patients. Such uses may be enable assessment and enhancement of cognitive ability, diagnosis of neurodegenerative diseases, prediction of aggression or early violence, detect deception and evaluate consumer marketing preferences. This in turn may lead to the expansion of the relatively new fields of neuroeconomics/neuromarketing, and neurosecurity. (See Table I.)

2) *Modeling and Reverse Engineering* is a major thrust of computational biology and bioinformatics [14,16]. Computing analyses of large volumnes of data from DNA, RNA and protein sequencing of the brain will become increasingly important to understand the molecular neuro-biology, as a component of neuroinformatics. The hardware typically consists of numerous, parallel high-end computers, while sophisticated software algorithms aim to incorporate the complexity of the neural

Table II: Neurotechnologies – Modeling and Reverse Engineering

- The NIH Blueprint for Neuroscience Research launched a $30 million Human Connectome Project (HCP) that will use cutting-edge brain imaging technologies to map the circuitry of the healthy adult human brain. [NIH, 07/15/09] [i]
- The Allen Human Brain Atlas is a genome-wide map of gene expression in the human brain that combines information about gene activity with anatomic knowledge. [Allen Institute for Brain Science, 2003] [ii]
- Hanson Robotics has developed the robotic Einstein to explore how a machine can perceive and react to human facial expressions, eye contact, face recognition and spoken conversation. [Smithsonian Magazine, 07/09] [iii]
- Neuromantic is a free application for the semi-automatic reconstruction of 3D models of neurons. [University of Reading, 03/31/08] [iv]
- The Fast Analog Computing with Emergent Transient States (FACETS) Project developed a chip that simulates the learning capabilities of the human brain. [MIT Technology Review, 03/25/09] [v]
- DARPA awarded US$4.9 million to IBM and its collaborators to develop 'Cognitive Computing' where electronic circuits mimic brains. [BBC Science & Environment, 11/21/08] [vi]
- Numenta is creating a new type of computing technology – Hierarchical Temporal Memory (HTM) - modeled on the structure and operation of the neocortex. [Guardian, 04/10/08] [vii]
- The Cybernetic Intelligence Group at University of Reading has developed a robot named Gordon controlled by a 'brain' formed from cultured rat neurons. [ZDNet, 08/13/08] [viii]
- Stanford University's Neurogrid carries out simulations large enough to include interactions between cortical areas, yet detailed enough to account for distinct cellular properties. [MIT Technology Review, 03/25/09] [ix]
- DARPA is investing US$ 3 million for the Systems of Neuromorphic Adaptive Plastic Scalable Electronics (SyNAPSE) program to develop a brain inspired electronic 'chip' that mimics the function, size, and power consumption of a biological cortex. [Wired, 02/07/08] [x]
- The €6.7 million European Union backed SENSOrimotor structuring of Perception and Action for emergent Cognition (SENSOPAC) project has built part of an artificial mouse brain. [Wall Street Journal, 07/14/09] [xi]
- The Harvard-MIT Complex Biosystems Modeling Laboratory has developed a multiscale agent-based 3D model for simulating brain cancer heterogeneity. [Mathematical and Computer Modelling, 05/24/08] [xii]
- The Blue Brain Project claims that a detailed, functional artificial human brain can be built within the next 10 years. [BBC Technology, 07/22/09] [xiii]
- CoTeSys and Fly-O-Vision have built flight simulators to study blowflies to build flying robots. [Wired, 07/31/09] [xiv]
- Project One is a US$ 3million National Science Foundation funded project that developed a humanoid robot CB2 which exhibits levels of complexity found in human infants. [Google News, 04/04/09] [xv]
- Decisions in Motion has developed a robot capable of moving autonomously using humanlike visual processing and object detection. [MIT Technology Review, 06/30/09] [xvi]

networks and their properties. Mathematical modeling of several variables, incorporating the analyzed data, is conducted for hypothesis-testing, and making predictions of system behavior, *in silico*.

Such computer simulations allow for experiments that can not be feasibly or ethically conducted in animals and humans. Robots are being constructed that not only mimic human activity in everyday settings, but allow use in dangerous environments. The development and construction of an artificially intelligent system that can learn, behave, perform, and maintain some level of autopoiesis, is the ultimate quest of paradigms that seek to reverse engineer the nervous system. (See Table II.)

3) *Brain-Machine Interfaces (BMI) and Prosthetics/Orthotics* are systems that operationalize the intersection of the nervous system and an internal or external device to effectively combine human and machine capabilities (14, 17). Characteristically, they are instruments (such as bionic limbs, cochlear and retinal implants, wheelchairs and synthetic speech software) aimed at restoring (i.e.- prosthetics) or enhancing (i.e.- orthotics) motor, sensory, communicative, or cognitive function.

BMI tools, such as transcranial and deep brain stimulation, are most often used in neurorehabilitation following stroke, paralysis, and/or traumatic brain and spinal cord injuries, although such technology could potentially be extended to affect- if not enhance- learning and memory. Alternately, *virtual reality (VR)*, a computer-based multi-sensory technology, can be used to manipulate the senses to give an alternate sense of reality, for example, in schizophrenia to help the patients distinguish between virtual and real worlds or training soldiers for combat.

Much innovative and commercial diversity is occurring within the field of BMI and neuroprosthetics. The fusion of human and non-biological elements is expected to continue into the future, so as to enact the iterative process of ‘cyborgization’ described- and predicted- by Clynes and Kline (26). This process, to a large extent, remains subtle.

Simpler devices or methods used in everyday life are more innocuous. Technologies such as memory storing devices (for music, documents and other information) and communication methods (cell phones, emails, GPS and the internet) all supplement human brain function. Yet, despite the relatively ‘simplicity’ of these tools, it is important to notice the technological convergence that occurs when different functionalities are combined into singular devices or methods. (See Table III.)

4) *Neuromics* broadly refers to the study and application(s) of genomics, proteomics and metabolomics in contexts of the nervous system structure and function (18, 19). Neurogenetics entails the elucidation of genetic mechanisms involved in normal neurocognitive function, and neurological (e.g.- Alzheimer’s and Huntington’s) and psychiatric (e.g.- depression) conditions. *Neuroproteomics* seeks to study those proteins involved in brain function, while *neurometabolomics* aims to identify metabolic processes engaged in and/or subvserving neurophysiologic and neuropathologic events.

Approxiately 10,000 genes (a third of the human genome), and three times as many proteins are putatively involved in brain function. Very few, if any, normal or abnormal brain functions reflect activity of a single gene or protein. Thus, the goals of these fields of genomics, proteomics, and metabolomics- to attempt modulation of existing genes, and/or insertion of, new genes, proteins and metabolites, by targeting specific regions of the brain to elicit a specific response, to treat or enhance brain function- remains daunting. Still, there have been some successes in narrowing the selection of possible candidate genes and proteins that affect predisposition(s) for specific conditions (e.g.- apolipoprotein E (ApoE) in Alzheimer’s; serotonin reuptake transporter (5-HTT) in depression; and brain-derived neurotrophic factor (BDNF) in learning and memory). (See Table IV.)

5) *Psychopharmacology* refers to the study, prevention, treatment of neurological and psychiatric or enhancement of psychological conditions through the use of drugs or pharmaceuticals (14, 20-22). There are a wide range of drugs; below are the conditions they are used most often for:

a. *Cognitive* disorders where learning, memory and attention could be affected as seen in attention-deficit hyperactivity disorder (ADHD) and Alzheimer’s (AD);
b. *Personality* disorders which makes social coping rather difficult as in schizophrenia and anxiety;
c. *Mood* disorders where there are fluctuations in the mental states of happiness or sadness of the individuals observed with depression and bipolar disorder.

Table III: Neurotechnologies – Brain-Machine Interfaces (BMI) and Prosthetics/Orthotics

- Cochlear implants, electronic devices that mimic the function of delicate cells of the inner ear, are approved for children under the age of 3 years. [LA Times, 08/03/09] [i]
- FDA approved DEKA's iBOT mobility system, whose self-balancing technology allows the user to go up and down staircases, navigate difficult terrain and "stand" at eye level with the ambulatory people around them. [USA Today, 08/14/03] [ii]
- The Boston Retinal Implant Project begins trials in 2010 for humans blinded by retinal degeneration. [MIT Technology Review, 07/25/08] [iii]
- Monkeys learned how to move a computer cursor with their thoughts using just one set of instructions [New York Times, 07/20/09], and a bionic arm to feed themselves [Nature, 05/28/08] [iv]
- Benefits of deep brain stimulation (DBS) were seen in Parkinson's patients over the age of 70 with only temporary side-effects. [Science News, 01/31/09] [v]
- Transcranial magnetic stimulation (TMS) is used to treat depression. [US News and World Report, 07/15/09] [vi]
- Carbon-fibre prosthetic legs, called Cheetahs, allow a South African double-amputee to compete with able-bodied runners. [BBC Sports, 05/16/08] [vii]
- Functional electrical stimulation (FES) is shown to improve limb movements in patients with spinal-cord injury or stroke -induced paralysis and help them walk. [The Scientist, 01/01/09] [viii]
- BrainGate's Bionic chip implanted in the brain monitors its activity and allows a quadriplegic patient to convert her intentions into commands on a computer. [ABC 60 Minutes, 11/02/08] [ix]
- Ossur Bionics' Proprio Foot is the first intelligent foot module that thinks and responds to changing terrain such as stairs, slopes, flat or soft ground. [x]
- DEKA's Luke, the most advanced prosthetic arm, received funds from Department of Veterans Affairs and DARPA for a 3 year study among veterans. [Popular Science, 06/01/09] [xi]
- CyberDyne's Hybrid Assistive Limb (HAL) along with Raytheon's Sarcos and Lockheed Berkeley Bionics' Human Universal Load Carrier (HULC) exoskeleton suits can expand and improve physical capabilities, such as strength, speed and endurance, producing 'super-soldiers'. [xii]
- Institute for Human and Machine Cognition is building the undersea Performance Improving Self Contained Exoskeleton for Swimming (PISCES) system. [Wired, 09/17/08] [xiii]
- DynaVox Xpress is the world's most powerful handheld augmentative communication device, with internet and visual scanning capabilities, for patients who cannot use their voice due to autism, amyotrophic lateral sclerosis (ALS), Down's syndrome or stroke. [Scientific American, 08/10/09] [xiv]
- The OZ cockpit display provides superior human-centered situational awareness and flight performance information for manned and UAV pilots. [Avionics, 10/01/03] [xv]
- Sensory substitution technologies, such as tactile glove, sonar canes, vOICe Learning Edition and Brain Port tongue interfaces, are helping blind people to see. [The Globe and Mail, 03/21/09] [xvi]
- A Japanese rail firm has introduced an Omron Okao Vision facial recognition and scanning system to check that staff are smiling enough at all times. [BBC News, 07/11/09] [xvii]
- AspireReader, is a software reader that improves reading and learning outcomes by providing access to digital talking books, Internet pages, and words for individuals with sensory and cognitive disabilities. [xviii]
- According to Common Sense Media, parents are out of the loop when it comes to their children's time on social networking sites such as Facebook, LinkedIn, YouTube, MySpace and Twitter. [CNBC, 08/10/09] [xix]
- Second Life is the largest free online 3D virtual world, one of the many massively multiplayer online role-playing games (MMORPGs), imagined and acted on by digital personas or Avatars created by its Residents. [xx]
- The Special Interest Group on Graphics and Interactive Techniques (Siggraph) conference has a virtual reality exhibit that is giving visitors the extreme ranges of sight and hearing that many animals have. [BBC News, 08/07/09] [xxi]
- Mattel teamed up with Total Immersion to develop a new line of toy action figures, based on the upcoming action sci-fi-film Avatar, which would incorporate augmented reality technology. [Tech Show, 07/23/09] [xxii]
- The Infantry Immersion Trainer (IIT), the Asymmetric Warfare Virtual Training Technology (AW-VTT) and the Tactical Field Care Trainer (TC3) are some of the virtual reality training programs employed by the US military. [PBS FrontLine, 04/29/09] [xxiii]
- The DARPA's Augmented Cognition program and Office of Naval Research's Warfighter Performance Department have funded Design Interactive to develop innovative technologies to measure psychophysiological changes, such as EEG, pupil dilation, mouse pressure, body posture, heart rate, and galvanic skin response, in real time. [Wired, 03/21/07] [xxiv]
- The Simbionix Mentor simulator line offers clinicians the most realistic hands-on experience performing Minimally Invasive Surgery (MIS) and interventional procedures, at no patient risk. [BBC News, 05/23/09] [xxv]

Table IV: Neurotechnologies – Neuromics

- Scientists have discovered the first gene involved in regulating the optimal length of human sleep. [Science Daily, 08/14/09] [i]
- Intracellular location of the protein degradation machinery, or proteasomes, may help in memory formation and loss. [Science Daily, 04/25/08] [ii]
- RNA interference (RNAi) mediated gene silencing was carried out in non-human primates. [Nature, 05/04/06] [iii]
- A study used high-throughput sequencing to uncover active genes in a mammal's early brain development, including those that contribute to neurological disorders. [Science Daily, 07/27/09] [iv]
- A Nature study has produced the most compelling evidence to date that genetics play a key role in autism. [BBC News, 04/28/09] [v]
- A global analysis of brain proteins indicates protein expression changes occur early in life and precede onset of Huntington Disease. [Science Daily, 04/21/09] [vi]
- The first genetically altered monkey model that replicates some symptoms observed in patients with Huntington's disease was developed. [Science Daily, 05/19/08] [vii]
- Three rare deletions in the human genome appear to raise the risk of developing Schizophrenia considerably. [The New York Times, 07/31/08] [viii]
- Transplanted neural stem cells produce Brain-Derived Neurotrophic Factor (BDNF) and may rescue memory in advanced Alzheimer's disease. [Science Daily, 07/22/09] [ix]
- An earlier study linking depression to a specific Serotonin gene is now faulted. [The New York Times, 06/19/09] [x]
- Mild oxidative stress, through hormesis, could prolong life. [Science Daily, 05/30/09] [xi]
- Estrogen can reduce stroke damage by inactivating a tumor-suppressing protein known to prevent many cancers. [Science Daily, 07/20/09] [xii]
- DOPAL, derived from Dopamine, is responsible for cell death causing Parkinson's disease. [Science Daily, 08/31/07] [xiii]
- Myelin genes appear to influence intelligence by determining the quality of the nerve axons which allow for fast signaling bursts in our brains. [Science Daily, 03/18/09] [xiv]
- The ability to measure glutamate levels in the brain over time provides an improved method for tracking Multiple Sclerosis and predicting its course. [Science Daily, 05/07/09] [xv]
- A region on chromosomes 1 could be responsible for modulating stress responses involved in complex behaviors like drug abuse. [Science Daily, 07/17/09] [xvi]
- The genes that play a role in adolescent insomnia are found to be the same as those involved in depression and anxiety. [Science Daily, 06/09/09] [xvii]
- A mouse model has been developed which exhibits seizures closely resembling those occurring with epilepsy in infants. [Science Daily, 06/07/09] [xviii]
- The 'jumping genes' that insert extra copies of themselves create diverse brain cells and can explain brain development, individuality and neurological disease. [Science Daily, 08/06/09] [xix]
- Melatonin, involved in circadian rhythms, can delay the first signs of aging in a small mammal. [Science Daily, 06/23/09] [xx]
- The American College for Medical Genetics has recommended testing for 29 disorders in new-born babies. [March of Dimes, Accessed on 10/09/09] [xxi]
- Ultrasound and amniocentesis are routinely used in pre-natal screening for Down syndrome and Spina bifida. [March of Dimes, Accessed on 10/09/09] [xxii]
- Pluripotent stem cells shown to generate new retinal cells necessary for vision. [Science Daily, 11/21/08][xxiii]
- There is a heritable component of happiness which can be entirely explained by genetic architecture of personality. [Science Daily, 03/06/08] [xxiv]

It should however be noted that these conditions are not mutually exclusive in that more than one function can be affected in a given condition. There is often comorbidity of disorders in terms of their etiology and pathology. For example a patient suffering from post-traumatic stress disorder (PTSD) may exhibit anxiety and depression while having difficulties with attention or memory. This has implications both for diagnosis and treatments where normality of mental health becomes blurred. Besides ingestion, drugs can be delivered to the nervous system via injection, topical application and inhalation. Currently, efforts are underway to employ nanotechnology for targeting drugs to specific regions of the brain.

In addition to pharmaceuticals drugs described above, other potential drugs include endogenous hormones like vasopressin and adrenaline that can have systemic effects through discrete pathways (21,22). Furthermore, nutritional stores and internet offer a variety of over-the-counter compounds - such as Gingko biloba, Aloe Vera, Ginseng, Carnitine, St.John's Wort, and Vitamins B, C and E - with purported medical benefits that may not have been scientifically studied or clinically validated. Lastly, people consume alcohol, coffee, chocolate and nicotine on a daily basis; and some indulge in illegal drugs like marijuana, ecstasy and heroin. While the chemicals in these drugs may provide acute benefits, long term use could lead to addiction and severe cognitive impairments.

Table V: Neurotechnologies- Psychopharmacology

- The FDA has approved a new drug called Saphris to treat schizophrenia and bipolar I disorder in adults. [WebMD, 08/14/09] [i]
- Taking antidepressants, such as Wellbutrin, Celexa, Lexapro, Prozac, Zoloft and Symbalta, can make young people more than twice as likely to feel suicidal. [Telegraph, 08/12/09] [ii]
- Rophynol, normally used for treating short-term insomnia, is also called "roofies" and abused as a date-rape drug. [BBC News, 02/04/99] [iii]
- Propranolol, before memory reactivation in humans, erased the behavioral expression of fear memory 24 hrs later and prevented the return of fear, with implications for PTSD. [Nature Neuroscience, 02/15/09] [iv]
- Modafinil (Provigil), prescribed for narcolepsy, and a dietary supplement – Ephedrine are used by pilots to stay awake and alert for up to 30 hours. [Scientific American, 12/06] [v]
- Nanoparticles successfully delivered Dalargin, an analgesic, to the brain. [Journal of Pharmaceutical Sciences, 04/27/05] [vi]
- Hydralazine, an anti-hypertension drug, was coated to nanoparticles which prevented damage to brain and spinal cord cells. [Science Daily, 10/02/08] [vii]
- Combination therapy of Memantine and Donepezil is better in prolonging cognitive decline in Alzheimer's disease. [Science Daily, 07/23/08] [viii]
- Pain-killer opiods, such as Oxycontin, Vicodin and Percocet, are being increasingly abused leading to major addiction.[DHHS-SAMHSA, 07/08] [ix]
- Adderall and Ritalin, legal stimulants prescribed for ADHD, are increasingly used by students seeking a competitive edge by reducing fatigue while increasing reading comprehension, interest, cognition, and memory. [Nature, 04/09/08] [x]
- Use of antidepressants use among U.S. residents almost doubled between 1996 and 2005, along with a concurrent rise in the use of other psychotropic medications. [US News & World Report, 08/03/09] [xi]
- Ecstasy (MDMA), known as the 'love drug', may help PTSD patients deal with their memories more effectively by encouraging a feeling of safety. [Science Daily, 03/10/09] [xii]
- A multipurpose nanotechnology tool for medical imaging and therapy is now available. [Science Daily, 08/06/09] [xiii]
- Scientists developed nasal spray containing Interleukin-6 to improve memory. [Science Daily, 10/02/09] [xiv]
- Intranasal delivery of Oxytocin increased positive communication between couples. [Science Daily, 10/09/09] [xv]

Targeted drug delivery is expected to improve considerably due to the advent of nano-particles. The available scientific research and clinical findings, the de-stigmatization of psychiatric conditions and their commercialization, the ease of access to psychiatric care, the relatively cheaper costs and the human urge to improve or enhance through psychopharmacology therefore presents us with the most pressing concerns such as safety, specificity, access, addiction, commercialization and regulation. (See Table V.)

Enhancement through drugs and related issues have been reviewed in detail elsewhere (27-34).

Discussion

Utilizing the scanning method, this paper has presented and categorized neurotechnologies into five categories- 1) Monitoring and Imaging; 2) Modeling and Reverse Engineering; 3) Brain-Machine Interfaces (BMI) and Prosthetics/Orthotics; 4) Neuromics; and 5) Psychopharmacology. We included representative examples of studies and products within each of these groupings along with a preview of future developments. In doing so, we hope to provide insights into the direction and pace of evolution of the field of neurotechnologies for futurists, scientists, engineers, clinicians, ethicists and policy-makers.

We emphasize that the categories described only serve to delineate the different strands, but in no way are implied to be mutually exclusive. On the contrary, they are necessarily related. Often, more than one technology can be employed towards a desired outcome. For example, there may come a time in the near future when a given condition, such as Alzheimer's disease, maybe predicted using fMRI and prevented or treated through gene silencing and nanodrugs.

Neurotechnologies, involve various degrees of invasiveness, and the ability to manipulate the nervous system (sometimes, irreversibly). While there are ethical issues, questions and problems that are common to the study and use of neurotechnology, in general, each technology raises somewhat different ethical questions with regard to perceived benefits, costs and harms. This in turn will determine its level of acceptance among the public. Some of the concerns are philosophical (e.g.- human identity); ethical (e.g.- autonomy and privacy); legal (e.g.- responsibility); scientific (e.g.- efficacy and safety research); economic (e.g.- commercialization); governmental (e.g.- regulation and weaponization); and socio-cultural (e.g.- equity, stigma and discrimination).

Scanning was performed entirely online. Consequently, the results are limited to these developments that were available on the internet. Moreover, the data are drawn from the public domain and do not capture those studies and products protected by proprietary concerns of private sector, or classified status of military research. The search engines, keywords and online results were all in English. This excludes results published online or offline in languages other than English. A logical follow-up to this study would be to incorporate database and translation tools for mining offline and non-English data.

Neurotechnologies have and will alter human activity through products and tools that can restore, sustain, and/or enhance human function. The use- or perhaps mere presence- of such tools, models, norms, and practices could change business, culture, economics, health and public security. This implies 'creative alteration' of the very foundations of individual and social life, and obligates the responsible handling of any neurotechnology as each possess some capability to affect the human condition.

There are numerous drivers and barriers to the development and diffusion of emerging neurotechnologies. Cost-benefit factors will largely affect the initiation, sustenance and availability of these technologies, and convergence appears to be evolving at an unprecedented pace. The rate and extent of development of such technologies will vary in different countries due to economics, public policy, and variations in need and capacity.

Therefore, it is obvious that legislation can enthuse or hinder technological initiatives. However, legistlative process is not uniform or universal. Traditional values, customs and religious views can often skew public (and governmental) opinion regarding research, development, and adoption of new technology.

Nations that are politically stable with sound economic policies would attract both domestic and international investors in neurotechnology. There is considerable concern that venture capical investment(s) in neurotechnology research and production in politically unstable governments could affect, if not determine, the focus, pace, and use of developments and products. This poses significant challenges in assigning intellectual property rights, setting standards and effectively regulating dual-use potential.

Education and R&D infrastructure will play a key role for countries to remain competitive in convergent technologies. At the same time, privacy will become a cause for concern between individual freedom and national security.

These factors emphasize the importance of both 1) acknowledging and addressing ethical implications of convergent neurotechnologies, and 2) engaging ethical discourse toward anticipatory and necessary corrective action that direct sound use of these devices among various stakeholder groups (government, industry, academia, professional organizations, media and the general public). A growing body of literature is dedicated to this ethical discourse (35-43) and although beyond the scope of this overview, it is vital that such ethical considerations proceed in ways that are commensurate with the pace, breadth, and scope of technological progress (44)

Conclusion(s)

The impact of neurotechnologies is increasingly evident in medicine, business, law, sports, arts and entertainment, and holds potential for both promise and peril. Any regard of such potential necessitates forecasting of the types and directions that current and proposed state-of-the-art neurotechnologies will assume.

Scanning is a first step of successful forecasting. The value of scanning is that it facilitates anticipation of future trends, and perhaps more importantly, enables planning and preparation. The accelerated pace of neurotechnological advancement and convergence warrants continuous monitoring and necessitates understanding of the impact that these developments- and their effects- might incur for individuals and societies, both in the short- and the long-term. These considerations are critical to inform and guide ethical aspects of public policy.

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Competing Interests

The author(s) declare that they have no competing interests.

Notes

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