NEURAL DEVICES

The future is now, but what does tomorrow bring?

Abstract

Though health and well-being are advancing, there is still much to be understood about the human body, especially as it relates to the brain and the nervous system. After a close look at how the field of neurology developed through the years, a careful evaluation is taken regarding challenges, advancements, future endeavors, and potential pitfalls.

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Introduction: Why Neural Implants?

Humans are living longer lives due to advancements in technology and medicine. But even with these advances, industrialized societies are still plagued by heart disease, cancer, and mental health issues[1] , among many other ailments.

Pharmaceuticals have come a long way in addressing patient ailments and, in some cases, even eliminating a disease. Surgery and other physical treatments have become less invasive and more precise, making a full recovery much more likely, especially when an issue is found and addressed early. In addition, acknowledgment of the role mental health plays in disease has allowed for another avenue of approach.

The above remedies can accomplish a lot independently and even more when joined for a multifaceted approach. However, as good as these treatments can be, there are downsides. There are side effects from medicine and surgery. A lifetime of being tethered to a treatment, though not ideal, is usually an acceptable byproduct of managing or beating a condition. And in many cases, though the outlook and sum effects are better than without the treatments, the quality of life is not the same as it once was.

But what if there was an additional approach that could eliminate side effects and more or less cure a disease? What if there was a way to give a patient more of their previous life back?

While they won't be able to solve every medical issue, neural devices have the potential to supplement and even surpass the work of the previously mentioned treatments. These implants have already impacted those with physical setbacks by allowing for brain-controlled prosthetics and cochlear implants to aid in hearing. And instead of pharmaceuticals, neural implants have been used to control seizures, treat chronic pain, and address tremors caused by Parkinson's disease and Multiple Sclerosis (MS).

Neurology and neurotechnology, in the grand scheme of things, have only just started to walk. With the confluence of rapidly advancing technology, computing, material science, and understanding of neural communication, the science of nerves and the brain will sprint, making advancements in neural implants that can give patients a life they want to live rather than a life they have to live.

How do Neural Devices work?

Neural implants (brain implants) are injected or surgically placed in the body. They connect to neurons (nerve cells) in the brain via electrodes. Information is passed from one neuron to another via chemical and electrical signals. Implants either record the electric signals or emit electric impulses to stimulate a nerve.

[1] "Our Biggest Health Challenges," National Institutes of Health, November 16, 2023.

Neural prostheses are like neural implants in that they both work by transmitting data to and from neurons. Neural implants connect directly to the brain, but prostheses do not. Prostheses will assist an impaired or lost function such as hearing.

Neural stimulators connect to nerves and deliver electrical impulses through electrodes and improve function.

The ability to stimulate a nerve, such as with an implant, prosthesis, or stimulator, can allow medical professionals to fix or hack a broken communication system.[2]

Below are several devices with descriptions of how they work, followed by figures demonstrating how the devices are implanted.

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[2] Waltz, Emily, "How Do Neural Implants Work?" IEEE Spectrum.

TABLE 1: DEVICES IN USE TODAY

Therapy/Implant	Purpose	How does it work?	Potential Future Uses
Deep Brain Stimulation, DBS (Figure 1)	Used to treat Parkinson's disease, dystonia, epilepsy, and obsessive-compulsive disorder	One to two leads are inserted deep into the brain and connect via wire to a small processing device in the chest. Pulses from the processing device can be adjusted using a hand-held device to control neural activity (e.g., seizures)	Tourette syndrome, pain management, Alzheimer's disease, dementia, depression, obesity, addiction, chorea
Sacral Nerve Stimulation/Modulation, SNS/SNM (Figure 2)	Incontinence, Parkinson's related bladder symptoms	Delivers electric impulses to the sacral nerve via a surgically inserted electrode to stimulate bowel, sphincter, and bladder muscles to work normally.	Sexual dysfunction, chronic pelvic pain[3]
Vagus Nerve Stimulation, VNS (Figure 3)	Epilepsy, depression, stroke recovery	A processing device is implanted in the chest, connected to a wire wrapped around the vagus nerve. Impulses at regular intervals are sent to the vagus nerve to prevent seizures, create new neural pathways, and change brain wave patterns.[4]	Rheumatoid arthritis, chronic headaches[5]
Cochlear Implant (Figure 4)	Improve ability to hear	A microphone and transmitter sit on the outside of the patient's ear, while a transmitter receives and sends pulses to the cochlea with electrodes from just under the skin's surface.	
Brain-Computer Interfaces (BCI) with Microelectrode Arrays (MEAs)*	Allow for regained function (e.g., speech, movement) with the help of a computer	After the MEAs and processing device are implanted, signals from the brain can be used to interact with a computer to spell words on a screen,	Regain function and sense of paralyzed limbs, regain vision, control robots remotely using thoughts

*MEAs are not widely used due to the invasive nature of the implant.

[3] Canagasingham, Ashan et al., "Sacral nerve neuromodulation: the past present and future."
[4] "Using Vagus Nerve Stimulation (VNS) for Depression: Is It Recommended?"
[5] Yang, Jeyul and Ji Hoon Phi, "The Present and Future of Vagus Nerve Stimulation."

FIGURE 1: DEEP BRAIN STIMULATOR

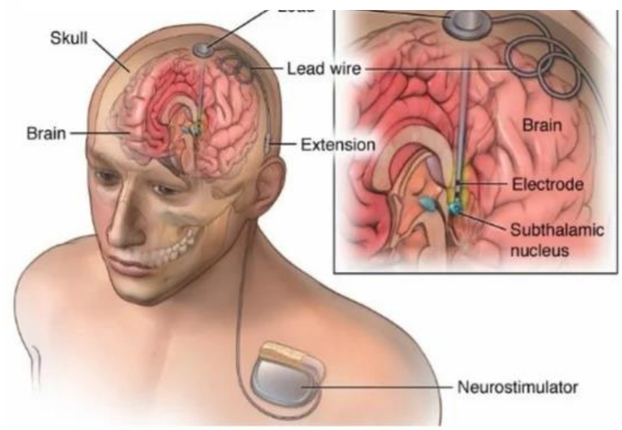


FIGURE 2: SACRAL NERVE STIMULATOR

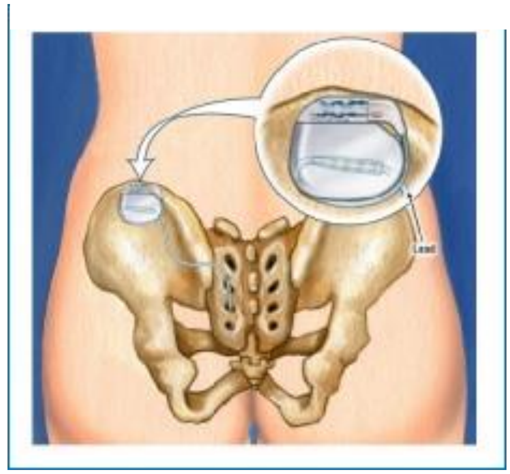


FIGURE 3: COCHLEAR IMPLANT

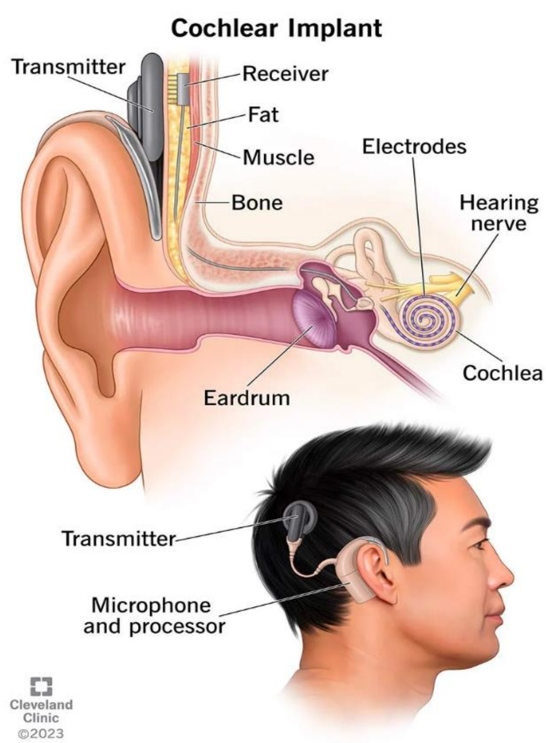
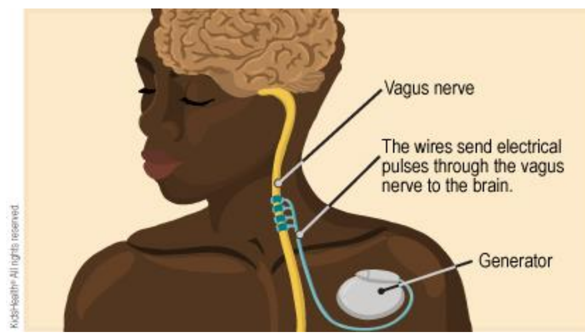


FIGURE 4: VAGUS NERVE STIMULATOR



While not widely used yet, microelectrode arrays (MEAs) and brain-computer interfaces (BCIs) allow patients to think something and have it happen. Such is the case with Pat Bennett, who, after losing her ability to speak from amyotrophic lateral sclerosis (ALS), and Ann, who lost her ability to speak after a stroke, can think what they want to say, and the computers produce the words[6].

History, Challenges, and Complications

Amazingly complex, the roughly three-pound brain is made up of enough neurons to equal the earth's population—times ten![7] It's been the subject of queries and probes for some time, though the progress has been slow until recently. Even though discovery in neuroscience, the study of

[6] Reardon, Sara, "Watch a person unable to speak for years 'talk' using a new brain implant."
[7] BrainFacts.org, "How Many Neurons Are in the Brain?"

the structure and function of the brain and nervous system, is explosive now, with each new advancement comes new questions and trials.

The Development of Neuroscience

The earliest documentation of the brain was found in the Edwin Smith Papyrus, where Ancient Egyptians from the seventeenth century BC shared surgical treatments and anatomical knowledge.[8] Though some of the finer details of the brain were yet to be understood, enough was known that warriors going into battle would often protect their heads.[9]

A surgical procedure to protect the brain has been seen in cultures all over the world and going back as far as Paleolithic times. This technique, trepanation, creates a hole in the skull to relieve pressure caused by a bleeding or swollen brain, clear the debris of a fractured skull, or to let "bad spirits" escape.[10,11]

In 1848, a gentleman by the name of Phineas Gage was working with a 1.1 meter long, 6mm wide tamping rod when a premature explosion caused the rod to enter his skull through his left cheek and exit through the top of his head with enough force to make him fly back several meters. Still conscious after, he could communicate with the doctor who came to the scene. He bled for two days, then became ill with a virus that left him semi-conscious for a month. In the fifth week, he recovered and, outside of being blind in his left eye, seemed no worse off than before the accident.

Figure 5: Phineas Gage with his tamping iron.

Figure 6: Skull of Phineas Gage

However, Dr. John Harlow, who had treated Gage from the beginning, noticed that while his memory seemed intact after his recovery, his personality had changed. Prior to the accident, Gage was energetic and looked up to for having a "well-balanced mind." [12] But Gage ended up losing his position as a foreman because of his obstinance and childlike behavior. Gage's chance injury, resulting in a personality change but no memory loss, was evidence of localization, that certain parts of the brain performed different functions.[13]

In the late 1800s, Camillo Golgi discovered how to color neurons, allowing them to be seen by microscope. Santiago Ramon y Cajal standardized the process, and the two men were awarded

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[8] Bem et al., "The Anatomy of the Brain - Learned Over the Centuries."
[9] Ghannaee, Fakharian, Sarbandi, "Ancient Legacy of Cranial Surgery." 72-74.
[10] Nikova and Birbilis, "The Basic Steps of Evolution of Brain Surgery." 297-05.
[11] Gross, "A Hole in the Head: A History of Trepanation."
[12] Harlow, "Recovery from the Passage of an Iron Bar Through the Head." 327-47.
[13] Ricardo Vieira Teles, "Phineas Gage's great leagacy."419-21

the Nobel Prize in 1906 for their work on the nervous system.[14] In 1924, Hans Berger observed distinct wave patterns with his new intervention, the electroencephalogram (EEG).[15]

The most significant strides in neuroscience came with the introduction of magnetic resonance imaging (MRIs) in the 1970s and much more so with functional MRIs (fMRIs) developed in the 1990s. MRIs allowed for detailed three-dimensional images of the brain, and fMRIs made it possible to see parts of the brain that were activated during specific tasks or thoughts. This insight has allowed scientists to observe changes in the brain over time, demonstrating both plasticity (ability to adapt and overcome) and degradation.

Scientists now know that there are more than 1000 types of neurons and that glial cells (support cells for neurons) do everything from chemical regulation to cleaning up dead cells, storing sugar, and helping information move faster.[16] Additionally, recent discoveries point to a bidirectional gut-brain axis, meaning there is a strong link between the digestive system and brain function.[17]

Challenges and Complications

Even when elements of a human neurological system are understood enough to create a device that could help fight off disease, address damaged tissue, or regain function, the device still must survive the human body. Unfortunately, the immune system is not a fan of any intruder, well-intended or not.

FIGURE 7: UTAH ARRAY BEFORE IMPLANTATION

When a foreign body, such as an electrode, is implanted in the brain, glial cells address the foreign body with an immune response, eventually encapsulating it. As a result, electrodes need to be replaced after several years. Finding a material that would minimize an immune response would allow for longer-lasting electrodes and less scaring of brain tissue.[18]

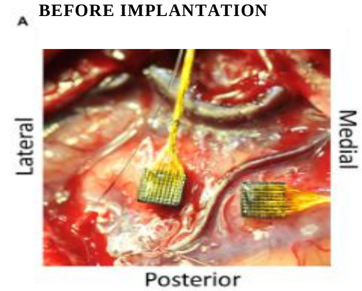

FIGURE 8: UTAH ARRAY

[14] Pietzsch, Joachim, "Speed read: Exposing the Forest." 2009.
[15] "A major breakthrough in brain implants." YouTube Video, 10:34, November, 28, 2022
[16] Dellwo, Adrienne, "What Are Glial Cells and What Do They Do?
[17] Appleton, "The Gut-Brain Axis: Influence of Microbiota on Mood and Mental Health." 28-32.

[18] Moshayedi et al., "The Relationship Between Glial Cell Mechanosensitivity and Foreign Body Reactions in the Central Nervous System." 3919-25.

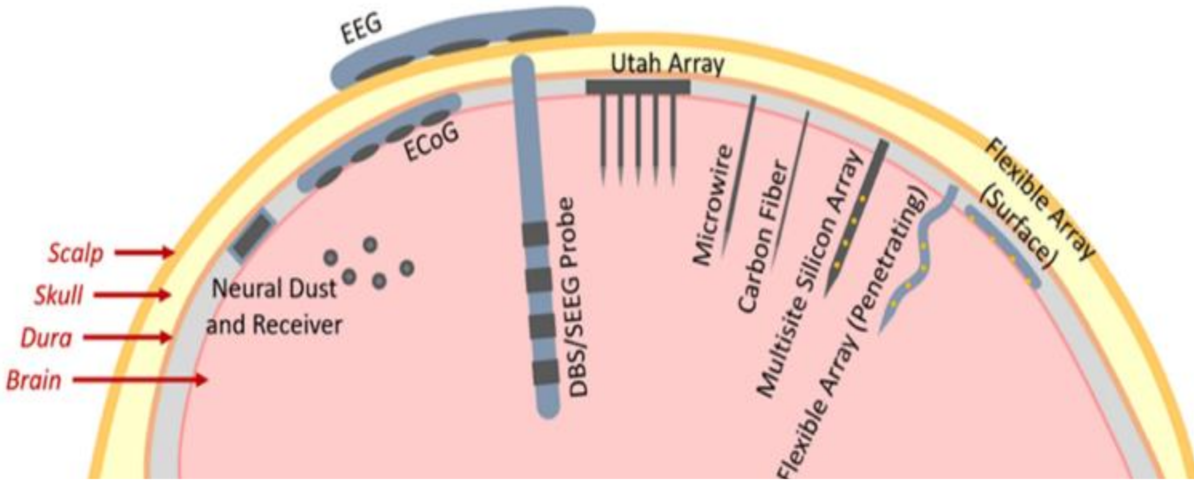

FIGURE 9: LOCATION AND SIZE OF DIFFERENT IMPLANTS

In addition to the composition of the material being used in implants, size and flexibility are also crucial. In some instances, the wires and electrodes themselves cause damage to the brain because they are physically probing brain matter (see Figure 9) [19]. In other cases, brain tissue can be damaged because of the nature of movement when a hard object is placed next to a soft one.[20]

Developments in Technologies

While the tools currently in use are making progress, there is room for improvement. Due to the invasive nature of many of the implants and the need to replace parts every few years, the risk vs. reward of having the implants seems to only benefit those who have very developed disease or loss of motor function. But, with new technologies eliminating or reducing the invasiveness of surgery and extending the time between updating components, there is hope that these neurological technologies can reach more of those who could benefit from them.

Artificial intelligence (AI) has exploded onto the scene in 2023. Its ability to synthesize large quantities of data in ways humans may not have conceived of before will allow for breakthroughs in understanding the human brain. For example, in a recent development at MIT, artificial neural networks using machine learning taught themselves to smell, mimicking the olfactory (smelling) circuits in a mammal brain—created in just minutes without any knowledge of the millions of years of human evolution.[21]

[19] Xu et al., "Recent Development of Neural Microelectrodes with Dual-Mode Detection."
[20] Huckings, Grace, "The Quest for Injectable Brain Implants Has Begun."
[21] "22 Amazing Breakthroughs in Neuroscience." Neurotracker. September 2022.

Developments in materials like hydrogels[22] (Figure 10) and nanotubes will make it possible to implant flexible, light, non-metal conducting substances.[23] Both would be more biocompatible than their predecessors and would cause less physical damage to the brain.

Until recently, most implants required major surgery, with cochlear implants being the exception, usually done as outpatient procedures and completed in a few hours. However, Synchron's Stentrode was developed to be non-invasive. Using a blood vessel in the neck, electrodes placed on a collapsible mesh, similar to a stent, are fed through a vein that sits next to the motor cortex (the part of the brain that controls movement), where it draws data and sends it to an external device.

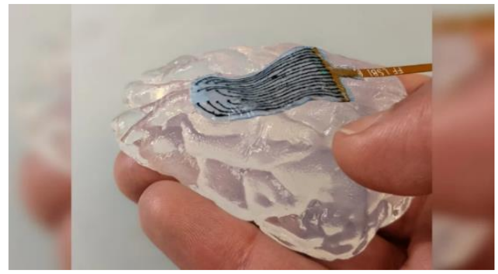

FIGURE 10 HYDROGEL WITH IMPLANT

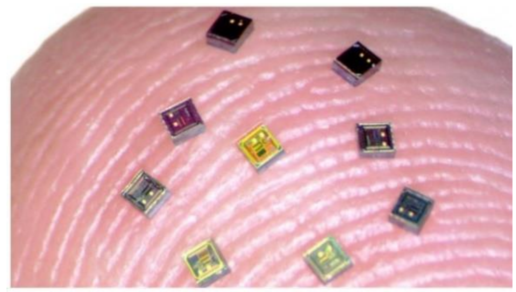

FIGURE 11: SALT GRAIN SIZED COMPUTERS

Computer processing speed has increased exponentially while the physical size of processors has decreased. Now, ultra-tiny computers the size of a grain of salt (Figure 11) can track brain activity and send wireless signals.[24]

Any of the above breakthroughs will allow for improved implants. Combined, they will surely make neurological devices more effective and less invasive.

Companies Leading the Way

The neurotech sector is trying to expand its understanding of the brain and reach more patients who could benefit from its products. Below are several stand-out companies making a name for themselves through innovation.

Neuralink's implant involves electrodes on threads surgically inserted by a robot using a needle smaller than the human hair. The threads that connect to the implant are designed to minimize damage during implantation and ensure long-term use. The battery is capable of being recharged wirelessly. It is intended to be cosmetically invisible and can control a computer or device anywhere.

Blackrock Neurotech's BCI and current NeuroPort array of electrodes lasts eight years with iridium-oxide electrodes and can be used for chronic and acute recording and stimulation. Their

[22] Bluestein, Adam, "This squishy material could be the next big step in computer brain implants."
[23] Malarkey, EB and V. Parpura, "Carbon nanotubes in neuroscience."
[24] "22 Amazing Breakthroughs in Neuroscience." Neurotracker. September 2022

Utah array was used in a study that restored some vision to a completely blind 57-year-old, allowing them to make out some letters and recognize some boundaries.[25] The company is focused on restoring broken brain-body connections, as seen with paralysis and neurodegenerative diseases, allowing the patient to move, feel, and even see again.

Synchron continues to work on endovascular brain-computer interfaces with technology like their stent-like electrode Stentrode (mentioned earlier). In addition to "restoring dignity to those with disabilities,"[26] they are creating and documenting patterns between movements and brain signals, which are consistent from person to person.

Kernel is dedicated to investigating brain markers with the help of AI and machine learning (ML) to draw up actionable insights.

Precision Neuroscience, co-founded by one of Neuralink's co-founders, developed a minimally invasive brain implant. With a millimeter-wide cut in the skull, an electron-filled film thinner than a human hair can slip in like a letter into a mailbox, where it easily conforms to the shape of the brain.[27]

What does the Future Hold?

The main goal of the companies listed previously is to improve the quality of life for those who suffer from disease or motor control loss. But in unlocking the secrets of the brain, a whole new world of function can be accessed.

Potential Outcomes

Below are just a few possible neural implant possibilities:

Super Soldiers Outside of exoskeletons and super blood, brain implants are another enhancement that could change how battles are fought. With a brain implant, a servicemember could control a drone hands-free on a battlefield and, with an internal heads-up display, have an account of all ammunition and location of friends and foes—much like playing Call of Duty—without having to take their eyes off of what is in front of them.

Super Hearing Humans can only detect a fraction of frequencies, but with new technology that would translate supersonic sounds, humans could hear as well as bats do.[28]

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[25] Fernández et al., "Visual Percepts Evoked with an Intracortical 96-channel Microelectrode Array Inserted in Human Occipital Cortex."
[26] Oxley, Tom, "Brain Implant That Turns Your Thoughts Into Text." TED2022, 12:42, April 2022, https://www.ted.com/talks/tom_oxley_a_brain_implant_that_turns_your_thoughts_into_text?language=en
[27] Capoot, Ashley, "Neuralink competitor Precision Neuroscience conducts its first clinical study to map human brain signals."
[28] "22 Amazing Breakthroughs in Neuroscience." Neurotracker. September 2022.

Increased Cognitive Function The noninvasive transcranial direct current stimulation (tDCS)[29] already attempts to increase neural plasticity to improve memory, learning, and problem-solving skills. But with a mini-computer implant, learning a language, passing the bar, or coming in first at the Scripps Spelling Bee would be a breeze.

Eternal Clarity and Cognition: What's the next step after stopping brain degenerative diseases? Stopping all cognitive and functional decline. Imagine being able to recall any memory or thought immediately. The only thing that would prevent living eternally would be the lifespan of the supporting tissue.

Cyberpunk and Jacking In Some would say fiction has inspired reality, such as in the cases of Jules Verne and H.G. Wells (no time machine just yet, though). But when it comes to matters of the brain, the cyberpunk genre has explored it all, particularly the concept of "jacking in."

Jacking in allows users to enter and interact with the internet through a neural implant and a wired connection. Cyberpunk usually occurs in dystopian societies with dark and ominous storylines. However, jacking in could be a great equalizer, bringing a brighter future rather than a dreary one. Regardless of their physical or socio-economic background, anyone could experience anything in existence and in their imagination. Outside of the initial surgery and jacking in unit, the other costs wouldn't differ from what one would pay for a streaming service.

Cautionary Notes

Many discoveries and new technologies surrounding neural implants come from a selfless place. Scientists want to stop the suffering of those with degenerative diseases and motor control loss. But if the technology leads from a primary goal of a net zero (back to normal function) to a net gain (enhanced function), is that okay?

Some get so caught up in discovery and breaking barriers that they neglect to see the path they are on or the dangers that surround them, much like the quote from Dr. Ian Malcolm in *Jurassic Park*, "Yeah, but your scientists were so preoccupied with whether or not they could, that they didn't stop to think if they should."[30]Just because something is bold and breakthrough doesn't mean it should get a moral or ethical pass.

[29] "What is transcranial Direct Current Stimulation?" Neuromodec. Accessed November 2023.
[30] "Ian Malcolm gives Hammond an ethics lecture." YouTube Video. 1:44, November 28, 2011, https://www.youtube.com/watch?v=4PLvdmifDSk from the film *Jurassic Park*, directed by Steven Spielberg and based on the novel by Michael Crichton. 1993, Universal Pictures, Amblin Entertainment. 127 min.

Below are some considerations to be made when thinking about advancements:

Cognitive, Motor, and Sensory Enhancement For an individual to receive enhanced cognitive abilities seems like a blessing. And it would be for the individual. However, when these enhanced individuals are grouped together, a superclass is born.[31]

When an employer is given a choice between a natural human and an enhanced human, they are choosing between a person with unlimited learning potential and total recall and a person who was late to the interview because they forgot where they put their keys. They are choosing between the detective who can smell like a bloodhound and the one who prefers the constant smell of cigarettes. They are making a choice between the firefighter who can lift three times their body weight while running upstairs at an eight-minute-per-mile pace and a person who struggles on those same steps with just their gear. Is there really a choice, especially when lives might be in danger?

Those who can pay for the enhancement will get ahead, and those who can't will be left behind unless there is an equitable and fair way to assign enhancements.

Privacy Though devices can't read thoughts yet, it's not for lack of trying. When they can, all that data, from the mental grocery list to the crazy thought about robbing a bank spurred by watching a movie, will be stored on a server. What if that information could be mined for passwords? What about using stored thoughts against someone in a trial? Or, on a positive note, mining someone's thoughts for clues in an unsolved mystery where the subject was a witness?

Before thoughts can be read, a comprehensive set of rules and laws must be created to protect individuals.

Manipulation Currently, neural implants can record neural activity and stimulate it with electrical impulses. This begs the question, if thoughts can be read, could they then be implanted?

If a person's thoughts are inherently bad—clinically psychopathic in nature—it could be prudent to install a device that manipulates these thoughts and keeps a killer from killing. But in most cases, installing thoughts is manipulation and taking away a person's free will.

Jacking In If one were to jack in, being able to tell the difference between reality and the online environment would be extremely difficult. It would be critically important to safeguard those more open to persuasion. Age limits would be needed to provide young minds the time to understand reality before diving into a virtual world. Mental acuity tests would be needed. Not because one would have to have a certain level of intelligence to enter, but because the complex

[31] Zehr, E. Paul, "The Potential Transformation of Our Species by Neural Enhancement."

mind is fragile, and at a certain point, a person could be convinced their virtual world is their real one.

Conclusion

Neural implants have only recently become a tool for change in the world of degenerative disease and motor function revival. Though currently limited by technology, material science, and a narrow understanding of the brain, the field's potential for growth is exponential.

With smaller and more powerful processors, wirelessly rechargeable batteries, non-metal electrodes, less invasive operations, and AI to analyze all the data, there's no reason to think that those who lost the ability to talk, walk, feel, or smell won't be able to restore all their lost functions. There's hope that with the data being pulled and processed, the cause of neurodegenerative diseases will be found and stopped, and how the brain and nervous system work will be fully understood.

However, the application of this knowledge can come with risks and dangers. As wonderful as the positive aspects of these advancements could be, there are also negative attributes. Patients, consumers, scientists, and governments must take notice of the possibilities now and prepare for what comes next.

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Figure 1: Concept of deep brain stimulation, taken from Nordi, Tiago Matheus, Rodrigo Henrique Gounella, Maximiliam Luppe, João Navarro Soares Junior, Erich Talamoni Fonoff, Eduardo Colombari, Murilo Araujo Romero, and João Paulo Pereira do Carmo. 2022. "Low-Noise Amplifier for Deep-Brain Stimulation (DBS)" *Electronics* 11, no. 6: 939. https://doi.org/10.3390/electronics11060939

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