Brain-Machine Interfaces: Treating and Decoding the Mind

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract

Brain-machine interfaces (BMIs) are devices designed to send information to and from the brain, essentially by reading and writing electrical signals with a neural implant. This technology has a vast array of possible applications in the future, but is still in its early stages of development. Today's BMIs are mainly designed for medical purposes — for example, to enable control of assistive devices and prosthetics, and for the study and treatment of brain disorders. The possibilities behind tomorrow's BMIs are under provocative speculation. This paper explores the current and future capabilities and limitations of brain-machine interfaces, outlines their ethical implications, and underscores the significance of their continued development.

BMIs have undeniably improved the quality of life for countless victims of debilitating neurological conditions. This technology has proven its ability to enable paralyzed individuals to communicate, interact with their environment, and even use their own limbs again. Much work needs to be done before neural interfaces can become a reliable answer to some of the more nuanced disorders of the brain, but they have shown promise in this regard as well. As innovations inevitably ensue, the industry must take great care to ensure the protection and security of its users' health, private information, and sense of personhood. Nevertheless, brain-machine interfaces are relevant not only as a tool for treatment, but as a means of precisely observing and decoding brain activity — to improve our understanding of harmful neurological conditions and the language of our neural circuitry as a whole.

Brain-Machine Interfaces: Treating and Decoding the Mind

Introduction

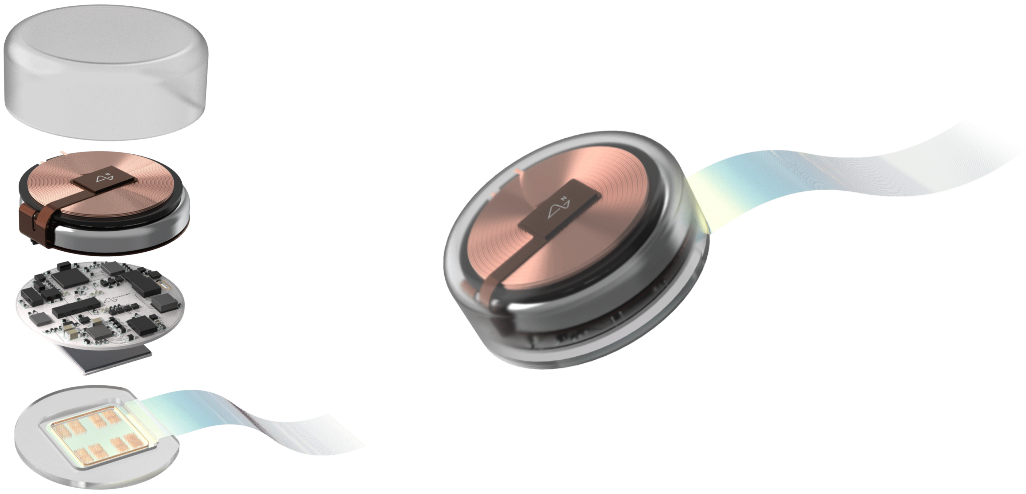
Amidst discussions of developing flying cars or colonizing Mars, it can be easy to forget that one of the most puzzling frontiers for human progress is our understanding of the brain. Indeed, much human strife is derived from ailments of the brain. Strokes, Parkinson's, and ALS leave many individuals paralyzed and unable to communicate or interact with their environment. Depression greatly hinders the quality of life for countless people, yet experts still struggle to precisely decode its underlying neural mechanisms. Drugs are being used to address many such problems — like stimulants for ADHD, or opioids for chronic pain. Yet, these medicines can yield unpleasant side effects, and even beget neurological illnesses of their own — like addiction. Almost 50,000 citizens died from opioid overdose in 2019, and around 80% of heroin users were originally misusing prescription opioids (National Institute on Drug Abuse, 2021).

Furthermore, some patients cannot even find relief from established drug-based treatments in the first place. It is for this reason that Dr. Philip Starr, a neurosurgeon at the University of California, took a different approach for his patients suffering from Parkinson's disease — by implanting electrodes in their brains. "We have people who, when they're not taking their meds, can be frozen," said Dr. Starr. "When we turn on the stimulator, they start walking" (Zimmer, 2015). This innovative form of treatment is just one example of a blossoming technological industry that could someday provide a reliable solution to address the vast array of prominent neurological conditions. The current face of this industry — Elon Musk — recently taught a monkey to play video games with its mind (Shead, 2021).

What Are Brain-Machine Interfaces?

Brain-machine interfaces (BMIs), also known as brain-computer interfaces (BCIs), use means such as implanted electrode arrays to record, transmit, and induce neural activity, essentially reading information from — and even sending information into — the brain. This technology exists today, but with limited capabilities and applications. Currently, the most well-established BMIs are used for medical treatment. For example, some robotic limbs are controlled by neural activity recorded from the brain's motor cortex. Cochlear implants record sound and stimulate the auditory nerve accordingly to restore hearing. There have even been successful experiments in rudimentary direct brain-to-brain communication between rats (Pais-Vieira, Lebedev, Kunicki, Wang, & Nicolelis, 2013), between humans (Grau et al., 2014), and even from human to rat (Yoo, Kim, Filandrianos, Taghados, & Park, 2013). However, current BMIs are only capable of transferring information with very limited fidelity.

Elon Musk intends to evolve the state of brain-machine interface technology with his venture Neuralink. The company is developing their own BMI, called the Link, which Musk likened to "a Fitbit in your skull with tiny wires" (Musk & Neuralink, 2020). By pushing the forefront of neural engineering, Neuralink seeks to first establish a foothold in medical devices, then build a scalable consumer-facing implant to essentially enable thought-powered computer control (Neuralink, 2021b). According to Musk, one great barrier to this innovation is the inability to record the activity of enough neurons. Neuralink hopes to push this boundary by developing BMIs capable of recording and inducing neural activity at an unprecedented level of fidelity. Their prototypes have seen success with rats (Musk & Neuralink, 2019), pigs (Musk & Neuralink, 2020), and even a monkey — Musk revealed Neuralink's accomplishment of implanting a neural interface into a monkey's brain, allowing him to play simple video games like Pong, using his thoughts instead of a controller (Neuralink, 2021c; Shead, 2021).



The Link implant (Neuralink, 2021a).

The Future in Your Head

Elon Musk has high hopes for the trajectory of the BMI industry, and has catalyzed much speculative dialogue about its future capabilities. A popular article by Tim Urban, featuring interviews with Musk himself, presents many bold assertions from the tech entrepreneur about the long-term prospects of BMIs, and generated public excitement about a future where thought replaces digital communication. Though the tool of neural interfacing is in its relative infancy, Musk hopes to guide its evolution towards something greater — a high-bandwidth, “whole-brain interface”, capable of understanding and transferring complex information and sensory experiences directly between human brains and computers (Urban, 2017). He claims that such an innovation would enable a more sophisticated form of communication than ever; with devices to decode thoughts from one brain and send them into another, humans would essentially communicate “telepathically”, rendering language obsolete. Musk believes that, since computers are capable of processing and transferring information much more efficiently than humans, a whole-brain interface would elevate our rate of communication to the rate of our own thinking. In Urban's (2017) article, Musk discusses the way modern human communication is bottlenecked by our physical limitations:

> There are a bunch of concepts in your head that then your brain has to try to compress into this incredibly low data rate called speech or typing. That's what language is—your brain has executed a compression algorithm on thought, on concept transfer. And then it's got to listen as well, and decompress what's coming at it. And this is very lossy as well. So, then when you're doing the decompression on those, trying to understand, you're simultaneously trying to model the other person's mind state to understand where they're coming from, to recombine in your head what concepts they have in their head that they're trying to communicate to you. ... If you have two brain interfaces, you could actually do an uncompressed direct conceptual communication with another person.

Musk and his colleagues are putting forth this and other ideas about what a network of fully-realized BMIs could enable, such as the ability to record full conscious experiences and relive them by "replaying" memories (Musk & Neuralink, 2020). One of the most provocative of such assertions, however, is that whole-brain interfaces could allow humans to augment their cognition with artificial intelligence. Musk believes that, as AI gets exponentially smarter and surpasses human cognition, direct brain-to-computer communication will prevent us from being "left behind", by enabling a "tight symbiosis" between human and artificial intelligence (Urban, 2017).

By framing the progression of neural interfacing as the next step for humanity, Musk has garnered much public support and excitement for Neuralink. However, some contemporary figures in the field of neuroscience are critical of his speculative rhetoric. A predominant criticism is that Musk's vision for the future operates under the major assumption that, not only will BMIs be able to precisely record and induce neural signals, but they will also be capable of decoding these signals to discern the conscious experiences they create, like seeing, thinking, and feeling. To this day, there is hardly any scientific understanding behind how those electrical signals manifest these subjective conscious experiences. Andrew Jackson, a professor of neural interfaces at Newcastle University, voiced his skepticism towards Musk's logical leap. "There is a big difference between recording brain cells and 'reading thoughts,' especially when it comes to higher-level cognitive functions we don't understand as well" (Morris, 2020).

Claims of a sci-fi future where telepathy replaces talking, while exciting, remain unfounded by scientific evidence. However, while Musk does envision this future, he emphasized in his 2020 demonstration that his immediate motivation is to generate support for the development of BMIs, and to recruit researchers, engineers, and other experts across scientific disciplines to aid Neuralink in making this progress (Musk & Neuralink, 2020). After all, Musk is an entrepreneur — he did not invent brain-machine interfaces, but he wants to use his platform to bring them into the public eye and build a business to fuel inspiration to push this boundary.

If Neuralink's initial goal were to bring about the age of human-AI symbiosis, it would be unlikely for them to gain enough support to bring that goal to fruition. Musk knows this, however, which likely influenced his decision to establish the team's footing in BMI applications considered more pragmatic in the short-term. Therefore, Neuralink's current focus is on the most tried-and-true of these applications: medical neural interfaces.

The Medical Capabilities of BMIs

The company's first mission is to develop interfaces to enable people with debilitating spinal injuries to control a computer with their minds. Soon, they hope to apply their tech towards "restoring motor and sensory function and the treatment of neurological disorders" (Neuralink, 2021b). Therefore, the Link is currently designed to engage with the exterior of the brain — the cortex — which deals with motor and sensory function. Going forward, however, the team aims to interface with deeper regions of the brain, which Musk says will be important for dealing with conditions like depression, anxiety, and addiction (Musk & Neuralink, 2020).

Giving paralyzed and disabled patients control of computers and prosthetics is a practical starting point, since this is the most well-established medical application of BMI technology. In their demonstration with pigs, Neuralink showed their implant's ability to accurately predict the intention to move limbs by reading neural activity (Musk & Neuralink, 2020). The same concept was used in their experiments with Pager the monkey — by using a joystick to calibrate the relationship between his brain activity and intended hand movement, the implant enabled him to play video games with his mind (Neuralink, 2021c). Logically, this capability holds great significance for the control of assistive devices. If an implant can understand what your brain activity looks like when you want to raise your hand, it can pass the command along to raise a robotic hand. In a recent interview, Dr. Leigh Hochberg of BrainGate — another notable neural interfacing research team with similar short-term goals to Neuralink — depicted a successful trial involving a patient suffering from stroke-induced tetraplegia. With a neural implant, she demonstrated the ability to control a robotic arm well enough to drink from a cup on her own volition (Hochberg & Unite Genomics, Inc., 2021).

“Drinking from a cup with a neurally controlled assistive robotic device by a person with tetraplegia” (Hochberg & Unite Genomics, Inc., 2021).

Using this technology to re-enable interaction with the outside world has crucial psychological benefits as well. Patients with locked-in syndrome noticed a substantial increase in quality of life after BMI technology allowed them to communicate, freeing them from the existential hardship of complete social isolation (Kübler, 2019).

The ability of neural interfaces to enable control of robotic limbs and assistive devices has been well-established, but in the long-term, Musk asserts that the industry can take this a step further; instead of controlling devices, BMIs could restore patients’ use of their own body. Musk explained that this would be done by using a second implant to create a “neural shunt”. For example, to treat a spinal cord injury, the first implant in the brain could communicate directly with the other implant at the base of the spine, in a way that bypasses the severed portion of the spinal cord. Musk compared a severed spinal cord with “broken wires” — if we can jump over the gap in the wires, we can pass the signals to their destination, restoring control of the patient’s own limbs (Musk & Neuralink, 2020). In fact, this very concept has been proven. After Ian Burkhart broke his neck, paralyzing him from the waist down, researchers at Ohio State

University fitted his motor cortex with a neural implant, allowing him to calibrate a decoder by thinking about moving his hand in various ways. Then, a series of electrodes can stimulate the muscles in his arm to produce the specific movements he thinks about, restoring Ian's control of his own hand. This cutting-edge treatment has rendered Ian capable of various fine motor tasks, including drinking from a cup, swiping a credit card, and even playing Guitar Hero (Stevens, 2018).

BMIs have already demonstrated their viability for enabling control of assistive technology, and even restoring lost motor function, but what about the plethora of neurological disorders which lie deeper in the brain than the cortex, and present deeper problems to solve? An existing form of neural interfacing, called "deep brain stimulation", has shown promise here. Deep brain stimulation (DBS), just as its name suggests, involves neural stimulation through more deeply-implanted electrodes. However, current instances of this technology are incapable of handling high-bandwidth information, and are not always consistently effective. Musk said that DBS is "sort of like kicking the TV" (Musk & Neuralink, 2020).

Despite its imprecision, however, deep brain stimulation has already provided effective treatment for many patients, especially those suffering from movement disorders. DBS has shown remarkable utility in treating Parkinson's disease, with around 100,000 patients receiving implants to mitigate their symptoms (Zimmer, 2015). Other established clinical uses include the treatment of essential tremor and primary dystonia. The FDA has approved varieties of deep brain stimulation for these purposes, and has also granted a Humanitarian Device Exemption for its treatment of obsessive-compulsive disorder. DBS has succeeded in treating Tourette syndrome, depression, and epilepsy. Additionally, it has shown experimental potential to treat headache, pain, vegetative state, addiction, obesity, dementia, and stroke recovery (Miocinovic, Somayajula, Chitnis, & Vitek, 2013).

CURRENTLY AVAILABLE TECH

8-16 channels per device

Valuable therapy for its uses, but cannot read or write high-bandwidth information

Destroys about a sugarcube of brain matter

Doesn't always work

Nonetheless, has greatly helped over 150,000 people

LINK V0.9

1024 channels per Link

23 mm x 8 mm

Flush with skull (invisible)

6-axis IMU, temperature, pressure, etc.

Megabit wireless data rate, post compression

All day battery life

Slides from Musk's Neuralink progress update demonstration, comparing DBS to the Link (Musk & Neuralink, 2020).

From Neurons to Knowledge

Thus far, existing iterations of brain-machine interface technology have demonstrated remarkable capability for the control of assistive devices by the motor cortex. Deep brain stimulation has been able to alleviate symptoms from a variety of neurological and psychiatric diseases for hundreds of thousands of patients, even in its relatively crude and imprecise form. Furthermore, Neuralink's current prototype is capable of reading and writing neural signals with much greater fidelity; while DBS devices utilize electrode arrays with up to 16 channels, the

Link boasts over 1000, and Musk hopes to continuously increase this figure by orders of magnitude (Musk & Neuralink, 2020). Given this promising trajectory, could BMIs feasibly become a reliable solution to these medical conditions in the near future?

This might be easier said than done, because there is still much to be understood about the nuance of the underlying neural circuitry behind these deep brain conditions. Dr. Philip Starr, who has successfully treated Parkinson's patients using DBS, emphasized this uncertainty. "We do D.B.S. because it works," said Dr. Starr, "but we don't really know how" (Zimmer, 2015). With this in mind, Musk's analogy of "kicking the TV" becomes all too accurate. Even with the ability to record neural activity at an increasingly great bandwidth, we are still faced with the challenge of decoding this activity. Writing for the MIT Technology Review, Antonio Regalado (2020) expressed his skepticism:

> The implant Neuralink is testing on its pigs has 1,000 channels and is likely to read from a similar number of neurons. Musk says his goal is to increase that by a factor of "100, then 1,000, then 10,000" to read more completely from the brain. Such exponential goals for the technology don't necessarily address specific medical needs. Although Musk claims implants "could solve paralysis, blindness, hearing," as often what is missing isn't 10 times as many electrodes, but scientific knowledge about what electrochemical imbalance creates, say, depression in the first place.

Even if brain-machine interfaces were suddenly capable of observing brain activity with complete fidelity, it would not accomplish much without a precise understanding of what that activity means. The path towards a reliable cure for these deep brain disorders is unclear, perhaps for the same reason why Musk's telepathic cyborg future remains in the realm of speculation;

science has yet to connect the dots between the brain's electrical activity and the subjective experiences that ensue.

Nevertheless, the forefront of this industry trends towards reduced uncertainty. Though DBS treatments, as we know them, are characterized by inconsistency, cutting-edge developments to this technology seek to introduce a more objective approach. For example, an emerging strategy for deep brain stimulation, known as "closed-loop programming", has been defined as "a dynamic adjustment of stimulation parameters based on a patient's current clinical status" (Miocinovic, Somayajula, Chitnis, & Vitek, 2013). In essence, this involves iteratively fine-tuning the induced stimulation (often with the aid of artificial intelligence) based on how the patient's condition and neural activity respond to it. Closed-loop DBS has been applied towards the pre-emptive detection and mitigation of epileptic seizures, and is also being used to model the experience of chronic pain, in order to develop treatments customized to individual patients (Shirvalkar, Veuthey, Dawes, & Chang, 2018).

Decoding the brain to understand how these deep-seated disorders function is no negligible task, and while a raw increase in BMI bandwidth will not solve this alone, it will yield more quality data for interpolation by experts, and perhaps more promisingly, by artificial intelligence or machine learning algorithms. To solve these problems, we not only need better technology, but a better understanding of the underlying science — but more sophisticated technology could open the door for this improved understanding. Neuralink co-founder Flip Sabes weighed in on this idea:

> The flip side of saying, "We don't need to understand the brain to make engineering progress," is that making engineering progress will almost certainly advance our scientific knowledge—kind of like the way Alpha Go ended up teaching the world's best

> players better strategies for the game. Then this scientific progress can lead to more engineering progress. The engineering and the science are gonna ratchet each other up here (Urban, 2017).

Essentially, as technological advancements beget an increasing quantity and quality of data, this data could provide further insight into the nature of these nuanced brain conditions, even if they are too complex for the human brain to solve alone. BrainGate's research in neurotherapeutics bears a resemblance to this reverse-engineering approach to decoding the brain's behavior. The team hypothesizes that the capability to precisely record neural activity will shed light on how exactly seizures begin in the brain, which in turn will pave the way for innovative treatment of epilepsy (BrainGate, 2021).

Neuroethics and the Cyborg Era

Widespread adoption of brain-machine interfaces is not without its ethical implications. One such concern is that the implantation of a BMI like the Link is an invasive procedure. The Link's implantation procedure is performed by Neuralink's own "Neurosurgical Robot", designed to precisely insert each electrode thread while avoiding blood vessels in the brain (Neuralink, 2021b). Indeed, Musk acknowledges the need for safe and easy installation and removal of the device. In his 2020 demonstration, he exemplified this by presenting Dorothy the pig, who, even after the successful removal of her Link implant, appeared "healthy, happy, and indistinguishable from a normal pig" (Musk & Neuralink, 2020).

Regardless, undergoing surgery to thread electrodes into the brain and replace part of the skull with an implant is inherently risky. There are indeed non-invasive examples of BMIs, such as fMRI and EEG, but they are nowhere near as sophisticated as implants. According to Krishna Shenoy, a Stanford professor working with neural interfaces, "Most in the field would [ask] if non-invasive performance can even begin to approach the level of performance of implanted sensors — most would say no, and by a lot" (Regalado, 2017).

Another important consideration is the security of this potential BMI network. Even today, there is public concern about tech companies collecting users' personal data and selling it to advertisers — often while obscuring the details from users. Even more alarming, however, would be a similar collection of data from users' own brains. If whole-brain interfaces come to fruition, the information within could be quite sensitive, and would need to be protected with unprecedented caution.

Perhaps the most chilling ethical implications, however, surround the effects of BMIs on their users' agency. Rare outliers among patients treated with deep brain stimulation reportedly underwent concerning changes in personality, including impulsive behavior, apathy, depression, and a distorted sense of self. "You just wonder how much is you anymore," pondered one such patient. "How much of it is my thought pattern? How would I deal with this if I didn't have the stimulation system? You kind of feel artificial" (Drew, 2019). Similar questions arise for neural interfaces using artificial intelligence to predictively control devices like prosthetics. With AI interpreting a person's intentions before they become actions, might these actions no longer solely derive from the person's free will? If not, then, could the person still truly consent to their continued treatment?

If these are relevant concerns today, imagine how human agency could be affected in a society communicating with whole-brain interfaces. With everyone's brain linked via the Internet, would the origin of one's thoughts and actions always be certain? Could a collective human identity emerge and replace individual agency? Furthermore, if this society augments their minds with a layer of artificial intelligence, like Musk envisions, would the people remain in control? Would the AI impose a different will? Or would a symbiotic identity emerge?

Even the satisfied users of brain-machine interfaces “refuse to be regarded as cyborgs” (Kübler, 2019). Most individuals likely share this sentiment, and would reject an identity that is not fully human. However, as one might deduce from his unflinching tendency to compare biology with technology, Elon Musk sees this differently; to him, this is already happening:

> The thing that people, I think, don’t appreciate right now is that they are already a cyborg. You’re already a different creature than you would have been twenty years ago, or even ten years ago. You’re already a different creature. You can see this when they do surveys of like, “how long do you want to be away from your phone?” and—particularly if you’re a teenager or in your 20s—even a day hurts. If you leave your phone behind, it’s like missing limb syndrome. I think people—they’re already kind of merged with their phone and their laptop and their applications and everything (Urban, 2017).

Musk asserts that we are already “digitally superhuman” — boasting digital enhancements allowing us to make unthinkable calculations and instantaneously communicate across the globe. Whether these enhancements are external devices or implants makes no difference to him. Adopting whole-brain interfaces, he argues, would simply allow us to more efficiently interface with the digital tools we have already integrated into our lives. Popular educational content creator Michael Stevens (2019), reflecting on the future of neural interfacing, had this to say about the ethical concerns surrounding the progress of technology and its deepening relationship with humanity:

> There is no such thing as a totally wild human. We are co-evolving with technology. Humans and technology today are inseparable. Now, it’s true that we need to be careful

> about every new thing we do, but we cannot change the fact that they will happen. It's a story we've lived through again and again. You know, we could have sat around forever debating whether or not a speed limit should exist and who should have the authority to enforce it. But we didn't. Instead, we went ahead and invented cars, and responsibly figured out the details as we went along. Ethical questions about new technologies do the most good when they facilitate the technology, not when they needlessly hinder progress (20:46).

Conclusion

Many of the sobering struggles that have plagued countless people throughout history are rooted in ailments and disorders of the brain. Though scientific and technological advancements have led us towards helpful breakthroughs, many of these problems linger with no reliable solution. However, brain-machine interfaces have proven their ability to address some of these problems like never before. This technology has undeniably improved the quality of life for many victims of debilitating neurological conditions, such as Parkinson's disease, locked-in syndrome, and stroke-induced tetraplegia. Much work needs to be done before neural interfaces can become a certain answer to some of the more mysterious disorders like depression and addiction, but they have shown promise in this regard as well.

Furthermore, as the industry progresses, the benefits of a potential neural interfacing breakthrough are worth pondering. If BMI technology establishes a foothold by proving its medical utility, and advances in line with optimistic speculation, society could make unprecedented achievements that can even benefit healthy individuals; one can only imagine the renaissance that would ensue if we could communicate complex ideas directly between brains and computers in a manner that would render human language obsolete (Urban, 2017). For this to happen, however, the industry must proceed cautiously, ensuring the protection and security of its users' health, private information, and sense of personhood.

Finally, even while managing our expectations about the near future's possibilities, we would be remiss to ignore the potential of brain-machine interfaces. If for no other reason, this field is worthy of pursuit because neural interfaces can give us an increasingly clear picture of how the brain works. Observing the brain's behavior in detail is a logical approach towards advancing neuroscience research, finding solutions to some of our most troubling problems, and even answering some of our biggest existential questions. The mere presence of this dialogue underscores one special quality that sets humanity apart from the rest of nature: our unparalleled drive to understand ourselves.

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