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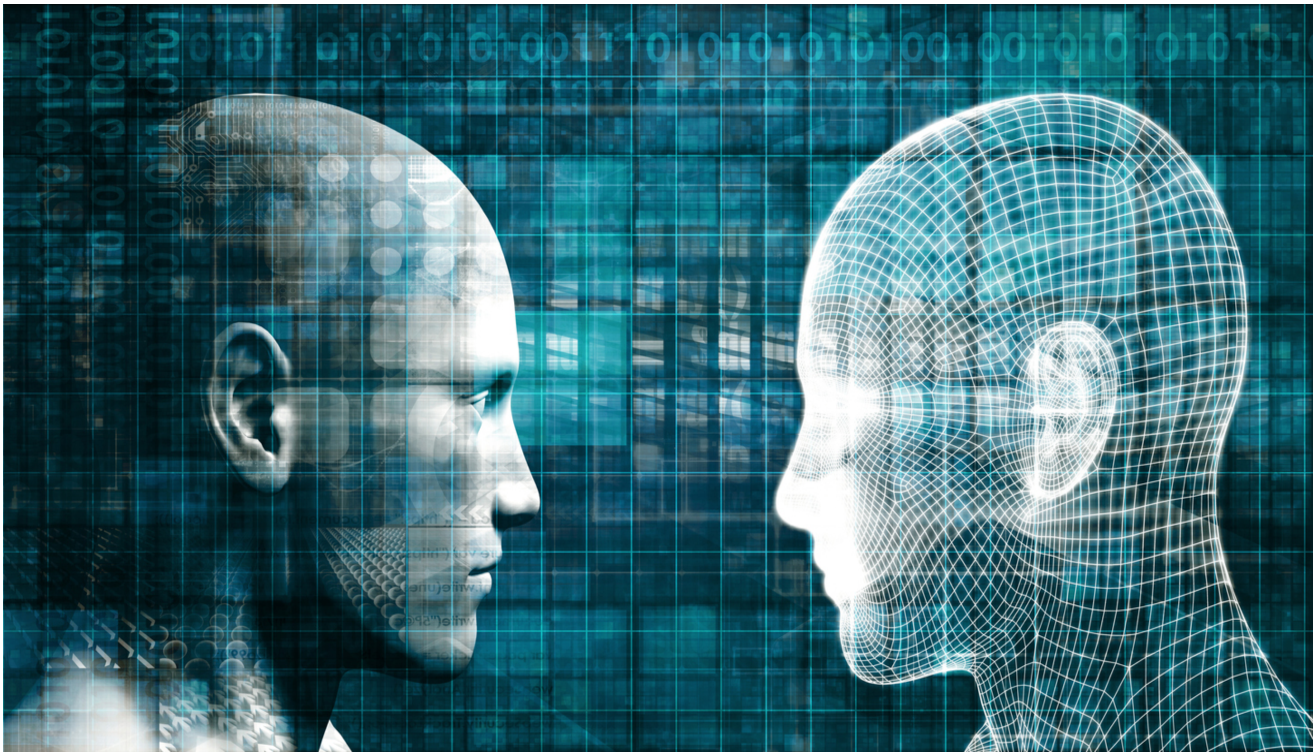

Brain-Computer Interface

Across decades, technology has advanced at impressive speed to award mankind a list of luxuries. Incongruous to this, is the link between Man and Machine. While the methods of communication between Man and Machine have evolved, they do not look very different from decades ago. Such communications have been incremental improvements to emulate the way humans communicate with one another. However, the path of incremental improvements has reached its limit. We can now speak to machines on the same proficiency as speaking to other people. For this reason, scientists have been exploring a radical way of communication. Specifically, a direct link between brain and computer – a brain-computer interface. Currently, this technology is still in its infancy but is already showing huge promise with applications ranging from medical to consumer products. Bigger strides have been limited to medical products due to technical, safety, and regulatory issues. This report takes a look at the early stages of the technology to get a glimpse of where it might end up in the future.

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What is a Brain-computer Interface?

A brain-computer interface ("**BCI**"), or brain-machine interface, is a device that facilitates direct communication between your brain and a computer. To understand what this means exactly, we can look at our current relationship with personal computers.

Currently, your fingers and keyboard are what enables you to communicate with your desktop. It helps translate thoughts in your brain to letters and numbers on the screen of your personal computer. For this same task, a BCI would enable you to type via thought. That, in essence, is what BCIs are – communication with computers by thought. It cuts through all intermediate communication processes and connects your brain *directly* to a computer.

This report will focus on new and exciting BCIs that are peering into the future. For instance, impressive BCIs are being developed in the field of medicine. They come in the form of robotic arms previously only witnessed in Science-fiction. However, keep in mind that such technologies are still nascent and face a plethora of challenges.

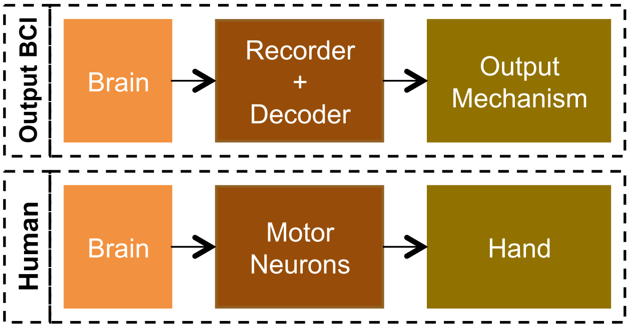
Following this, the report will delve deeper into several general classifications of BCIs and a brief history of neuroscience. This should serve as fundamentals to understanding the applications and problems discussed thereafter. In terms of BCI applications, two broad themes of medical and consumer BCIs will be covered. For the problems BCIs face, the report will discuss the technical, regulatory, funding, and ethical issues.

Output VS Input BCI

Naturally, communication involves mutual flow between two parties. Take the example of using your hands to explore a dark room. The process can be broadly broken down into two phases. First, your brain instructs your hand to move around to feel for objects of interest. Second, pressure receptors detect the object and sends this information back to the brain. These two processes are analogous to the two main categories of BCIs – Output and Input BCIs.

Output BCI

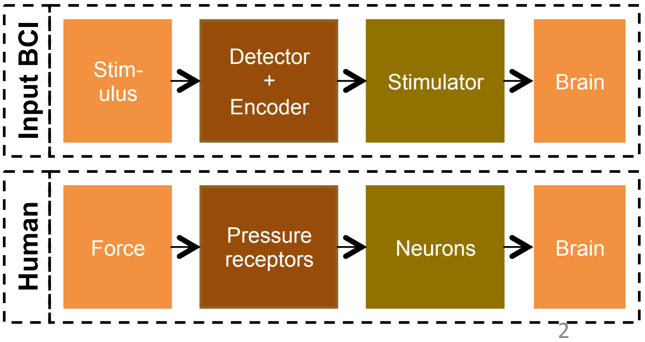
Output BCIs involve giving instructions to a computer via brainwaves, analogous to how you move your hand by thinking. They consist of the following components and information flow to function:



Source: SAC Advisors

Input BCI

Input BCIs involve a computer informing and stimulating your brain, analogous to how pressure receptors under the skin informs you of presence and information of an object. They consist of the following components and information flow to function:



Source: SAC Advisors

Whether the BCI is a output or input oriented, they both require intimate devices for recording and stimulating the brain respectively. The question here is – how intimate or invasive should this device be?

Non-invasive VS Invasive BCI

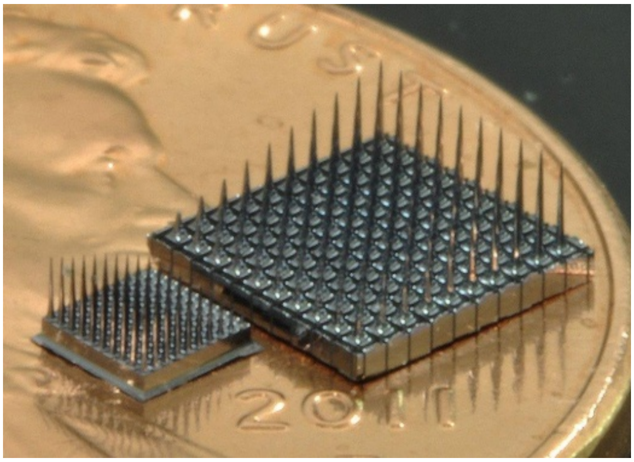
The Output-input BCI classification is based on functionality of the BCI. Alternatively, BCIs can also be classified via the locations of their recorders (in the case of output BCI) and stimulators (in the case of input BCI). They are termed non-invasive and invasive BCI.

What separates non-invasive and invasive BCIs is the locations of their recorders or stimulators. Non-invasive BCIs have its recorder or stimulator located outside the skull while invasive BCIs have theirs placed within the skull. Non-invasive BCIs come in the form a wearable to be placed on the head of the target personnel. An example of it is the electroencephalogram (“**EEG**”) cap, normally used in laboratories.

Electroencephalogram (EEG) Cap

On the other hand, invasive BCIs require neurosurgery for a recording device to be placed directly on the brain. The Utah Array is commonly used as the recording device in invasive BCIs. As seen below, the pin-like structures in the Utah Array are electrodes capable of detecting brain activity.

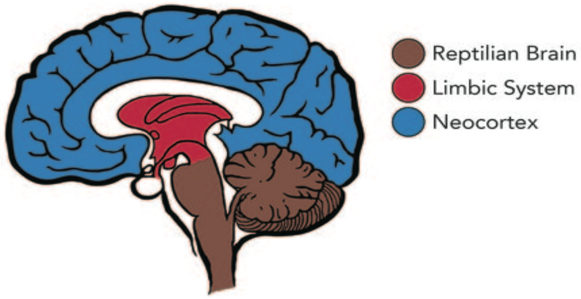
This distinction between invasive and non-invasive BCI may seem trivial for now. As the report progresses, the distinction will prove more meaningful.



Source: Utah Array

Our Brain

Before diving further into BCIs, it helps to understand some parts and functions of our brain.



Triune Brain Model *Source: PsychologyToday*

In the 1960s, neuroscientist Paul MacLean classified the human brain into 3 distinct parts as seen above. Maclean’s model, called the Triune Brain, was derived from earlier comparative neuro-anatomical studies. In other words, the model was crafted by comparing brains of other organisms. The methodology is reflected in the names of the 3 parts. For instance, the Reptilian Brain was named because comparative neuro-anatomists believed that forebrains of reptiles and birds were once dominated by this structure. The Limbic system is commonly found in mammals, on top of the reptilian brain. The neo-cortex was thought to be responsible for our intellect because of its unique presence in higher mammals.

The observations suggested a hierarchy among the parts. Through this, MacLean hypothesized that the limbic system and neo-cortex were structures sequentially added to the primitive reptilian brain through the course of evolution.

MacLean also localized brain functions into specific areas of the brain. He attributed instinctive fight-or-flight responses to the reptilian brain, emotions to the limbic system, and cognition to the neo-cortex.

While the Triune Brain model is apparent in popular culture, it is over-simplified. Its simplicity provides a good starting point for understanding the brain but has also led to certain misconceptions about the brain.

Common Misconceptions about the Brain

Humans currently use only 10% of our brains

This idea started with Harvard psychologist William James, who told audiences of a study that people only meet a fraction of their full mental potential. Thereafter, the idea incepted popular culture through the famed book by Dale Carnegie, How to Win Friends and Influence People, and morphed into the misleading quote. Recently, it served as the premise of the blockbuster film, Limitless.

In truth, humans use the entirety of our brains. If the claim was true, we would be able to remove 90% of our brains with no impairments. However, studies and history has shown that even slight damage to our brains causes profound impacts.

Each structure of the brain serves one specific function

This idea of fixed-structure function mapping is expressed by the Triune Brain model but is no longer espoused by majority of neuroscientists. Instead, neuroscientists now suggest that structure-function relationships are dynamic and context-dependant. In other words, each structure is involved in a myriad of brain functions.

Emotion opposes cognition / Emotion is the lesser of cognition / Emotion is irrational

This view is largely still under debate but was recently espoused by majority of neuroscientists. Regardless of the form of each assertion, they all express a conflicting duality in emotion and cognition. However, neuroscientists propose that emotion and cognition are partners on a similar mission rather than saboteurs. The idea of conflicting duality partially evolved from the hierarchy in brain structures and localization of functions established in MacLean's Triune Brain. Accordingly, the "higher" neo-cortex's cognition is looked more favourably upon than the “lower” limbic system’s emotions. The idea was also promulgated in popular culture via the Stoics of ancient Greece and Victorian society favouring restraint of emotion in tough situations.

Majority of neurologists have rejected MacLean’s proposed hierarchy in brain structures and its implied hierarchy between cognition and emotions. Instead, they theorise that cognition and emotions both play important parts in helping us perceive and react to the environment.

Following is an excerpt from a paper demonstrating the interplay between cognition and emotion.

“Mr. Smart slams on the brakes when noticing the proximity of the car in front. Anger arises initially from frustration, as Mr. Smart wants to keep driving fast, but also from a sense of violated entitlement: he is in the left lane and should not have to slow down. Fear may also be triggered by the close call, eliciting further anger because of an intermediate evaluation of unmanly helplessness. These emotions arise rapidly, but they are paralleled by a co-emerging sense of the other driver as intentionally obstructive (and therefore blameworthy). Mr. Smart’s highly focused visual attention, a derivative of anger, takes in the red colour of the car ahead, as well as the expensive-looking design, and his anger is amplified by his sense of the unfairness of this show-off blocking his path (based on an implicit memory of some long-forgotten or fantasized rival). A stabilizing angry-anxious state , coupled with ruminative plans for vengeance (perhaps a blast of the horn), anchors attention to the head of the man in front. This lasts for a minute or two while Mr. Smart fashions and modifies plans to pass on the right. However, when the man peers over his shoulder, Mr. Smart evaluates this act as a taunt, generating shame and anger in an elaborated appraisal of humiliation, and calling for extreme action to save his self-image from further subjugation.”

In the example above, emotions and cognition continuously and mutually reinforce one another in a cycle. Whether Mr. Smart’s thinking is petty or wrong is besides the point. Emotions arise for a reason, and a big cause is cognition. It seems that the limbic system is only adapting by emoting, according to the world we conceive by cognition.

Current State of Neuroscience

The debate on conflict between emotion and cognition may give us a rough idea of our primitive understanding of the brain. The idea has been promulgated centuries ago, but we still do not have a clear answer to it. This is not to say neuroscience is largely useless, because it has proven capable of miraculous feats such as brain surgeries. However, the useful information we know about the brain truly pales in comparison to what we do not know.

Leading neuroscientist and Stanford professor Krishna Shenoy thinks our current understanding of the brain is similar to humanity’s understanding of the world map back in the 1500s.

World Map in 1507 *Source: National Geographic*

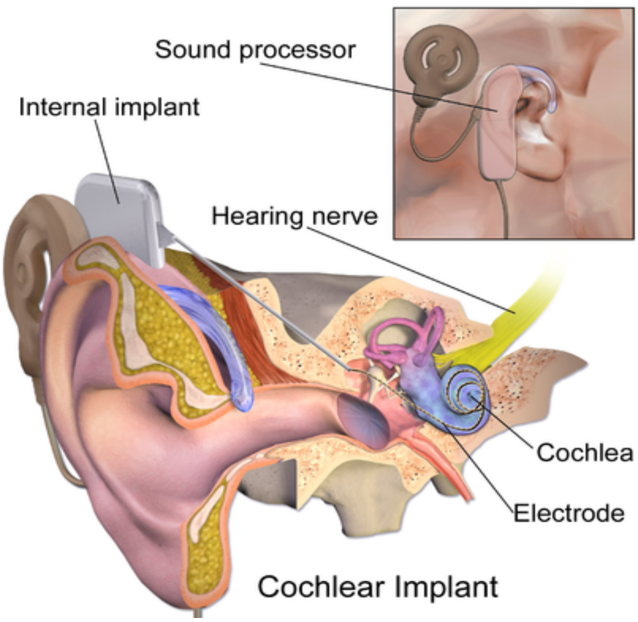
Neuroscientist Moran Cerf expressed an old saying in neuroscience that cleverly suggests why understanding the brain is so difficult. “If the human brain were so simple that we could understand it, we would be so simple that we couldn’t”.

Medical Applications of BCI

BCIs are an alternative form of communication with computers. Earliest forms of communication with computers were mechanical and appeared in the form of printed cards. Today, we have advanced mechanical communication into more fluid forms with keyboards and touch screens. Further, we have ventured into aural communication as seen in various voice assistants of Apple, Google and Amazon. One way to think of BCIs are a form of communication with computers that subverts any mechanical or aural disability in humans. From that perspective, medicine would be the obvious field to gain from BCIs.

Cochlear Implant

Cochlear implants give the sense of sound to patients with severe hearing loss. They bypass the ordinary acoustic hearing process in healthy humans and instead, rely on electric hearing. Sound from the environment is recorded through a speaker outside the ear, processed by the sound processor, transmitted to the internal implant, and finally used to stimulate the cochlear nerve via electrodes.



Source: Medline Plus

Visual aid

The Argus II Retinal Prosthesis System is a visual aid developed by NASDAQ-listed Second Sight Medical.

Argus II by Second Sight

Source: Second Sight

A camera in the goggles records moving images. The device at the patient's waist processes this data and transmits it to an implant located within the skull. Finally, electrodes attached to the back of the retina give the patient a sense of sight. The Argus II only alleviates a specific cause of blindness from a group of genetic visual disease known as Retinitis Pigmentosa. Patients suffer from damaged photoreceptors, meaning that light captured in the eye cannot be processed into images. The pictures below provide a rough gauge of what it looks like through an Argus II. Users only see in black and white, meaning they can only vaguely perceive high-contrast environments. The image perceived is somewhat adequate in definition but nowhere near high quality definition. Clearly, the Argus II is still not advanced enough to mimic an actual eye and Second Sight insists that it should be used along other visual aids such as walking canes.

Patient's sight with Argus II

Healthy person's sight

Source: New York Times

Robotic Limbs

Robotic limbs can fill the void for disabled personnel who have lost entire limbs in accidents or diseases. Dr. Andrew Schwartz, a neurobiologist at the University of Pittsburgh, is a pioneer of such robotic limbs. Dr. Schwartz has contributed to two major breakthroughs in the field. First, he has installed a functioning robotic arm on a patient paralysed from the neck down. The patient, Jan Sheuermann, had surgery for electrode implantation under her skull and subsequently underwent months of training to command control of a robotic arm. Following that, she was able to perform simple, everyday tasks such as shaking hands and picking up objects.

Jan Sheuermann feeding herself a chocolate bar

Source: Live Science

Second, Schwartz has enabled a patient to experience the sense of touch via a robotic arm. The patient, Nathan Copeland, received roughly the same procedure as described previously. On top of that, the robotic arm also has touch sensors connected to Copeland's sensory cortex. When tested, he was even able to distinguish between specific fingers that were touched.

Spinal injury recovery

BCIs can also help paralysed patients recover motor control of their limbs. In October 2018, The New York Times reported of 3 previously-paralysed men who were able to walk again with spinal implants. Traditionally, moving your limbs require the transmission of electrical signals from the brain, to the spinal cord, and eventually to motor neurons and muscles the limbs. When paralysed, patients lose this ability. The procedure circumvents this process via implanting electrodes in the spinal cord to receive electrical signals from the brain. Then, the signals are transmitted to a pacemaker-like device implanted in the abdomen to stimulate motor neurons in the target limb. While this procedure was miraculous, the patients were already capable of feeling some form sensation in their legs before the operation. Nevertheless, they were still ultimately paralysed.

David Mzee, one of the three previously paralysed men

Source: New York Times

Consumer Applications of BCI

Recording Device

Recording devices serve the exact, plain function its name suggests. An example is the EPOC+ by EMOTIV. The EPOC+ is an EEG that records your brain activity to give you data insights about your brain. Measurements come in the form of different bands of brainwaves that are associated with different feelings and emotions. For the consumer, this may help users monitor changes in their emotional states. Developers and companies also use these devices as a stepping stone to other applications discussed below. As covered in the introduction of output BCIs, recording devices are required for brain data collection before one can decode and make sense of the data.

Meditation Aid

Meditation aids are largely similar to basic recording devices, but they go a step further in marketing its use. For example, a product called Muse translates its users' mental activity into different sounds of the weather to guide meditation. The product is similar to meditation apps available to current smart phones but improves user experience by processing information on the user's mental activity as feedback for more tailored meditation guidance.

Open ended Software Applications

This category of BCIs provide its users a platform to develop useful software by utilizing the brain's information recorded by the provided hardware. This is similar to how the iPhone enables independent app makers to develop apps for all iPhone users. Mindwave by NeuroSky is an example of such a platform. Currently, Mindwave hosts 129 apps ranging from blink readers for the disabled to simple games. In the pile of 129 apps also lie developer tools for Mac, Windows, iOs and Android Operating Systems. Like Apple's App Store ecosystem, this will serve as the breeding ground for budding developers to explore new applications and test them in the market.

Muse, meditation aid

NeuroSky Mindwave

Gaming

Neurable, a BCI-focused startup, is developing a BCI to be incorporated into virtual reality games. Its current prototype works with the HTC Vive virtual reality headset. Neurable has also showcased a demo game called 'Awakening', that
it hopes to release soon. Utilising the wonders of BCI, the game casts the player as a child with telekinetic powers whose objective is to escape captivity as a government test subject. Before the game starts, the player must undergo a calibration process to get acquainted with the controls. During calibration, Neurable's headset studies and maps out different brain patterns to its corresponding objects in the game. This way, players will be able to execute in-game commands simply by thinking.

Subject playing 'Awakening' on Neurable's device

Source: MIT Technology Review

Future BCI

Beyond games and in the macro-view of Virtual Reality ("**VR**") and Augmented Reality ("**AR**"), BCIs done right could also propel innovation in those fields. Specifically, a large advance in our understanding of the brain could see our interactions with VR and AR change completely. For example, the traditional method of perceiving reality through our eyes could be circumvented. Instead, we could simply 'see' with our minds. Such a process could be similar to how we perceive dreams.

To explore the future, far-out possibilities of BCI, one can look at Elon Musk, the founder of Tesla and SpaceX. Musk started Neuralink in 2016 to connect humans and computers with high bandwidth BCIs. Previously, Musk has rallied for regulation of Artificial Intelligence ("**AI**") because he foresaw a possible future where AI evolves dangerously beyond our control to threaten the interest of humans. His warnings were ignored potentially because AI's dangers are eclipsed by its immense potential. The result – Musk could not persuade authorities to regulate AI. In a way, Neuralink is Musk's alternative solution his fatalistic view of AI. To beat future AI, Musk thinks we must achieve seamless human-machine symbiosis. However, a large roadblock sits in our way because current methods of communicating with a computer are far too slow. The most common way of communicating with a machine today is via our fingers. Be it typing on a keyboard or touch screens, Musk thinks mechanical communication is far too slow. Instead, he believes the solution lies in cutting out all intermediate communication processes and linking brain to computer directly. If that were achieved, it could pave the way for radical transformations such as human telepathy and instant learning via downloading data into our brains.

Problems with BCI

Complexity of the Brain & the Subject

As explained earlier in the current state of neuroscience, there remains much we do not know about the brain. A single brain is already amazingly complex on its own. But the problem is compounded when brain patterns are constantly changing, and each brain is different from another. This possibly implicates future BCIs to be either mass produced but limited in applicability to select people or tailored uniquely to suit the individual. Rob Jacobs of Neurable expressed similar sentiments and said that, "brain-interface technology simply doesn't work with some people. The brain is just really complicated."

Aside from the brain, the subject of BCIs is complicated as well. It demands fierce innovation from neuroscience, neurosurgery, electrical engineering, biomedical engineering and computer science. A successful BCI will need to tap on knowledge from numerous fields and apply them in new, unique ways.

Privacy, Safety & Regulation

For invasive BCIs, users will have or potentially have data from their brain recorded 24/7. Users might be uncomfortable with this level of round-the-clock surveillance. However, the invasion of privacy is fundamentally unavoidable in many circumstances, especially when data is the prime resource. In these cases, the question morphs into – is the upside worth giving up your privacy? Imagine a futuristic medical chip implanted in your head that monitors everything in your body and pre-empts you at the first sign of disease. Benefits of such technology would radically hasten disease detection because our current personal indicators are lagging indicators. Currently, we only see a doctor when we experience obvious distress commonly in the form of pain. For conditions such as cancer, seeing the doctor only when you first experience extreme pain would already be too late.

In such a case where BCIs provide unparalleled benefits, consumers would probably be willing to relinquish privacy.

Other than privacy concerns, potential recipients of invasive BCIs might also be opposed to the installation procedure itself. Placing a chip in your brain would sound terrifying to the majority because brain surgeries are risky. Choosing an invasive BCI entails a gamble between life and technology. Most likely, invasive BCIs would continue to be confined to patients who already have aspects of life compromised in some way.

Currently, invasive BCIs are only allowed on patients. If similar risks remain, there is no good reason for authorities extend access to the general population. Doing so would irresponsibly expose the public to the dangers of reckless neurosurgery. This is especially important because invasive BCIs are superior to non-invasive BCIs in functionality. The current applications of each BCI type is a testament to the disparity between them. Among the BCI applications covered previously, the impressive medical BCI and simplistic consumer BCI can also be split alternatively, into invasive and non-invasive BCI respectively. The superiority of invasive BCIs has to do with the quality of data recorded. Data recorded by non-invasive BCIs are largely dampened by the skull and thus not as useful as their invasive counterparts. Invasive chips can also be inserted in fixed, precise and intimate parts of the brain which non-invasive devices simply cannot do.

Invasive BCIs Expire

As miraculous as they may be, current invasive BCIs will stop working a few years after its installation. Jan Scheuermann, the recipient of the robotic arm mentioned previously, reported deteriorating dexterity in her robotic arm after 2 years. During the period, Scheuermann gradually lost the ability to open and close the thumb and fingers of the robotic arm. The cause – the chip installed in her skull became inept at recording neurons over time.

In detail, scar tissue formed around the electrodes of her brain implant, which desensitised it. The phenomenon is a common response of the brain in dealing with foreign bodies such as the chip. Further, BCI deterioration is not exclusive to Scheuermann, and has been widely observed across animal test subjects. Beyond this, the issue also exacerbates the issue of risk and regulation. A device whose efficacy is short-lived makes the tradeoff in risk more unpalatable.

Funding & the Isolation to Academia

The nascence of BCIs has confined many of its innovations to academia. Arguably, it has yet to reach the critical point where corporations are convinced of its functional and economic viability. The field faces the age-old conundrum where funding is needed to accelerate results, but there are no results satisfactory of funding. Fortunately, the dynamics could soon be changing with the recent inception of companies such as Neuralink and Kernel. Elon Musk has a track record of tackling complex, risky problems avoided by others and backs it up with necessary funding. The BCI community remains excited to see the changes these companies behold.

While academia does an adequate job in deepening understanding of the field, one lacking aspect seems to be the hardware. For example, invasive BCIs have been utilizing the same chip implant, the Utah Array, for 20 years. Problems with this lie in the buildup of scar tissue as explained earlier. Although the Utah Array might be only the size of a thumbtack, it is still too large. Neuralink might be able to solve this issue with the help of one of its co-founders, D.J. Seo. Seo previously worked at the University of Berkley on a concept known as 'neural dust'. The idea involves inserting thousands of tiny silicon motes under the skull which are capable of recording and transmitting data via acoustic vibrations.

Irresponsible Communication of the Future

Corporations and leaders of technology have the responsibility of being grounded in their communications about the future. Their position of authority commands considerable faith in the watchful eyes of the public, and it would be irresponsible and unethical to misrepresent an inflated version of reality.

In particular, Facebook and Elon Musk have given highly questionable completion dates for speculative technology. Speculation on the possibilities of BMI has merits in discussion, but they have promised an unrealistic timeline for the public to expect imminent arrival of speculative technology.

In Facebook's case, they proclaimed in April 2017 that they will be launching a non-invasive BCI in *two years*. The device will capable of transmitting sentences from your brain to your computer at a rate of 100 words per minute. Earlier in 2017, Stanford Professor Krishna Shenoy led a team to set a brain-typing record of 8 words per minute. Shenoy accomplished the feat with an *invasive* BCI and it took them a *decade* of work. In correspondence, Shenoy himself cited doubts in Facebook's claim. Further, he explained that there was consensus in the community that non-invasive BCIs were inferior in performance to invasive BCIs by a long-shot. In essence, Facebook promised to deliver unprecedented technology within an extremely short period, without any methodology or evidence to back its claim.

Elon Musk proclaimed that within 8 to 10 years, healthy people could be receiving brain implants as BCIs. Musk claim is unreasonable for reasons unlike Facebook's overly optimistic target for functionality. Musk's claim is unreasonable because it brushes aside the regulatory barriers *healthy* people face in receiving brain implants.

Antonio Regalado, the senior editor for biomedicine at MIT Technology Review, provided a regulatory timeline which makes Musk's timeline seem unreasonable. A company called NeuroPace started developing a brain implant to control epileptic seizures in 1997. This device aimed to solve a medical condition in which brain surgery was commonplace and hence relatively safe. However, it took NeuroPace 16 years to receive regulatory approval. For Musk to obtain regulatory approval for *healthy* people, his proposed procedure would also need to be radically different from the status quo and boast safety evidence an order of magnitude higher. The gargantuan challenge he faces does not warrant such an optimistic timeline.

Concluding Note

The possibilities of BCIs are extraordinary and its horizons are ever-expanding. In the medium term, eyes are focused on what the current, inspiring medical applications might evolve to tomorrow. Further, it would be exciting to see how the entrance of serious capital shakes up the BCI scene. On the other hand, consumer applications are rather underwhelming and have yet to shake off its perception as merely 'toys'. The sentiment is yet another repeat of how great technology begins. It is reminiscent of the public's aversion to the first personal computers in the 1970s. Consumer applications face greater barriers than medical applications in the form of safety and regulation. Understandably, regulators cannot give the green light to commercialize a life-threatening, temporary procedure regardless of how inspiring the benefits might be.

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