Reading your mind – Inside and out

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ABSTRACT

How do we know how the brain works? Doctors cannot just open your skull like a jar of candy and close the lid afterward… or *can* they? In fact, putting electrical wires, or electrodes, into human brains has been officially approved for many years. These devices, termed brain-machine interfaces, can help us record electrical signals from the brain and tell us how the brain interacts with the world. Researchers have leveraged this technique to improve the quality of paralyzed patients' lives and build game prototypes that are controlled by the brain. Though powerful, brain-machine interfaces are still facing many challenges. A guidance is also provided for Young Minds who would like to enter this field.

- What do you mean by “reading a mind?”

In the 18th century, Luigi Galvani applied electrical stimulation to a dead frog’s legs causing the legs to contract. This phenomenon gave way to the field of electrophysiology which is a branch of biology that deals with electrical signals in the body such as the brain. A neuron’s cell membrane has a resting state potential when the neuron is not excited by any external electrical signals. When the neuron is excited by an electrical signal, and the cell membrane potential (i.e., the electrical charge difference between the inside and outside of the cell) of the neuron exceeds a threshold, an action potential fires and travels along the neuron’s axon (i.e., the tail-like nerve fiber that directs the electrical impulses away from the cell’s body) and sends a signal to other neurons or muscles. This is how electrical stimulation makes the muscle twitch in the dead frog’s leg! Since then, researchers have begun to investigate the formation of movement activity, cognition, and memory in a person’s brain. To study activity across various neurons and brain regions, action potentials are captured using sensors called electrodes. By placing electrodes on the skull or inserting them into brain tissue, these electrodes allow us to collect brain signals and the user’s intentions. For example, when you wake up in the morning and begin to walk, interneurons (i.e., neurons in your brain) generate action potentials which are sent to the motor neurons (i.e., neurons that carry action potentials from the brain to the muscles) in your legs used for walking. What if your arms and legs are paralyzed? You can still think about walking forward, backward, left, and right, but you cannot complete these tasks on your own. Brain-machine interfaces (BMIs) communicate with a computer and/or external device (e.g., a wheelchair or robotic prosthetic) and detect patterns in a user’s neural signal to decipher and execute the user’s intention (Fig. 1). In other words, BMIs can control external devices using the user’s imagination as if the BMIs can read the user’s mind! With the help of BMIs, people with paralysis and amputations can partake in everyday tasks and regain some of their independence.

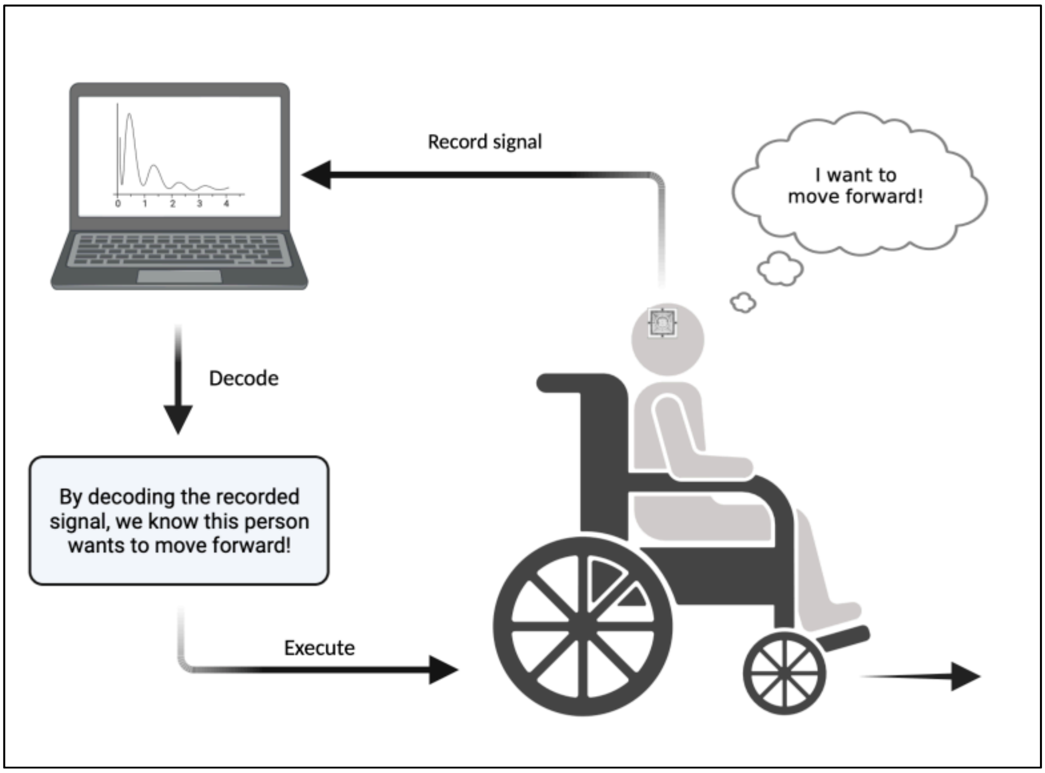

Figure 1. Patients with paralyzed legs can still think about moving forward. The brain-machine interface record signals from the brain. The signals are decoded so that the computer understands the intention of that person. This information is then executed on the wheelchair to move forward.

- What does a BMI look like?

Figure 2 shows the basic building blocks of a BMI [1]. To understand user intention, the BMI system must first record neural activity (i.e., action potentials) with electrodes. There are non-invasive and invasive types of electrodes. Non-invasive electrodes do not require surgery during electrode placement, whereas invasive electrodes do require surgery to implant the electrode. Electroencephalography (EEG) is a non-invasive method that measures potential changes on the surface of the scalp. Electrocorticography (ECoG) is an invasive method that requires drilling a hole in the skull to measure potential changes on the surface of the brain. Intracortical electrodes are an invasive method where the electrode is placed inside the cerebral cortex to measure potential differences within deep brain areas. Although invasive methods require surgery, they have higher spatial and temporal resolutions, which means we can more accurately pinpoint where neuron activity originates on a faster time scale than non-invasive methods. Once the electrodes record neural activity, the neural activity is analyzed so that we know which task or movement the user plans to perform. The onboard computer then translates the neural patterns to device commands that execute the user's intended task. For example, the user might want to control a mouse cursor on a computer screen, move an electric wheelchair forward, or close the hand of a robotic arm. Now imagine you are using a

BMI to close the hand of a robotic arm, but you cannot feel, see, or hear the arm closing. When there is a lack of sensory, visual, or auditory feedback to the BMI this is called an open-loop system. When feedback is provided to the user, this is called a closed-loop system and allows both the BMI but the user to learn better.

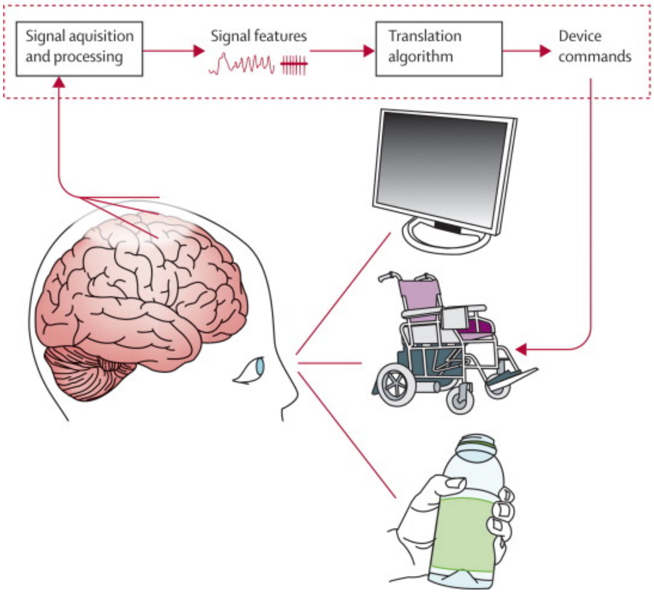

Figure 2. The basic building blocks of a BMI. Electrodes (either invasive or non-invasive) are used to record neural signals from the user. Once the neural signal is acquired and analyzed for signal features (patterns), the user's intention is translated to device commands which can be used to control various external devices (e.g., the position of a mouse cursor on a computer screen, the direction of a wheelchair, and grasping motion of a robotic arm).

➢ Can I Drive a Car Using a BMI?

BMIs have many applications ranging from health care to entertainment, and they are all dedicated to making people's lives better. BMIs can be used to control wheelchairs, grab objects, and even communicate with other people [2]. Researchers are working on combining existing and new computer games with BMIs to allow users to control the game with only their brains. Some researchers have created a virtual-ball movement game that requires no physical interaction with the computer [3]. The movement of the ball is controlled only by the brain signal of voluntary movements from the user collected using a BMI. This means we can eventually say goodbye to normal game controllers such as a joystick or keyboard. Along with no longer using conventional game controllers, researchers are also looking forward to a future without using your hands or feet to drive. Nissan has already begun working on a driving system that would record a driver's neural activity using an EEG device to anticipate a driver's intended movements while driving a car [4]. This is a very complex process that would require continuous processing of the user's brain activity in real time. This computing process that hasn't been created yet would be needed to fully let someone's brain control a car. The brain is very powerful, so hopefully, science will catch up one day, and we will get to the point where we can all drive a car using a BMI.

- How do you test if the device is effective and safe?

For all kinds of medical devices (e.g., BMIs) or medications that are eventually applied to human beings, a clinical trial is necessary to ensure safety and effectiveness. Let us take BMI as an example. Clinical trials allow researchers and doctors to assess the functionalities of the BMI and document BMI-related side effects in humans that cannot be achieved in animals or in labs. For example, Dr. Leigh Hochberg reported the first BrainGate (Cyberkinetics, Inc.) trial where a patient suffering from tetraplegia was implanted with a 96-microelectrode array in a brain region called primary motor cortex [5]. The patients moved a prosthetic arm by simply imagining that they were using their own hands, and the computer read the neural signal and translated it into prosthetic arm movements such as reaching and grasping. Even though the process seems straightforward, the device must first be validated in animals, such as rodents or non-human primates (NHPs), before beginning validation in humans. NHPs are especially critical for the development of BMIs since their brain anatomy and decision-making process closely resemble humans. Also, scientists need to incorporate healthy subjects in their experiments to verify the efficacy of the device, which is easier for NHP experiments but much more challenging for human subjects. In conclusion, the device must be tested in animal models first, and then move on to carefully designed clinical trials to guarantee safety and effectiveness.

- What are some challenges in this field?

The first challenge of BMI is the longevity of the device. Since BMIs are mostly invasive and some are even implanted in cortical areas, it is critical to reduce the frequency of surgical operations to minimize infection risks. The implanted device also needs to fight against signal deterioration and limited power capacity. Researchers have been advancing electrodes to be more biocompatible [6] and enabling wireless charging to reduce the frequency of surgery [7]. Second, the researchers must design a robust algorithm to decode the brain signal and identify the key brain region(s) of interest for recording. Just like we have different daily moods, the computer algorithm developed on one day does not guarantee the efficacy on another day. Therefore, the algorithm needs to be calibrated or even adapted to the current state of the brain. Third, the goal of a complete BMI is to incorporate sensory information so that the subjects can adjust their movement or decisions based on the information from the environment. This can be achieved by delivering electrical stimulation to corresponding areas in the brain or the periphery, such as the muscle fibers of an arm. In conclusion, there are still many unsolved challenges regarding the software and hardware of BMIs.

- What Should I Learn to Dedicate to this field?

If you wanted to dive deeper into the world of BMI, you could start right now. There are many free resources dedicated to teaching children about the brain. Reading scientific journals, such as Frontiers for Young Minds, will help keep you up to date with new scientific discoveries in the field. Another resource is BrainFacts.org which is a public information website dedicated to advancing brain research. The website has several fascinating articles about the brain separated by grade level which can be beneficial for maximizing your understanding. Learning about programming and signal processing will also help you gain a better understanding of BMIs. BMIs take signals from the brain, and it is crucial that we have a way of understanding what those signals mean which is why programming and signal processing skills are needed. Looking into the future, there are also classes that you can take at your local high school that would be beneficial for developing a background in neuroscience. For example, biology, anatomy, physiology, and computing classes would all help introduce you to different things that may come in handy when pursuing the BMI field later.

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GLOSSARY

1. Resting State Potential: the electrical charge difference across a neuron's cell membrane when the neuron is not excited by any external stimuli (a neuron's resting state membrane potential is approximately - 70 mV).
2. Action Potential: the rapid increase and then decrease of electrical charge difference across a neuron's cell membrane after excitation causing the neuron to generate an electrical impulse that travels down the neuron's axon.
3. Tetraplegia: a term to describe the inability to voluntarily move the upper and lower parts of the body.
4. Microelectrode arrays: devices that contain multiple electrodes where neural signals are obtained or delivered.
5. Sensory information: information that the brain collects from your senses (e.g. taste, sight, smell, hearing, and touch) that helps us understand the world around you.