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EXPLORING THE WONDERS OF THE BRAIN BY DIRECTLY CONNECTING IT TO A COMPUTER

Eilon Vaadia *

ELSC: The Edmond and Lily Safra Center for Brain Sciences at the Hebrew University of Jerusalem, Jerusalem, Israel

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AGE: 13

Imagine controlling your favorite video game just by thinking about it! While this might sound like science fiction, this incredible technology is becoming a reality thanks to brain-computer interfaces (BCIs). BCIs enable communication between the brain and an artificial device. Picture your brain as a powerful machine that sends electrical signals when you want to do something, like controlling a robotic arm with your mind after losing the ability to move your hands. BCIs transmit brain signals to a computer, which then learns to understand those signals and translate them into instructions that control the device. In this article, we explore a world where minds and machines interact, and the possibilities are limited only by our imaginations.

THE BRAIN WORKS THROUGH NEURONAL NETWORKS

The brain is the most intriguing organ in the body. Throughout evolution, it has developed in ways that allow it to perform complex computations, from which all of our behaviors arise. The brain is composed of billions of cells, known as **neurons**, that are interconnected by **synapses** in vast **neuronal networks** (Figure 1; to learn more, see this Frontiers for Young Minds article). Imagine yourself as one little neuron communicating with 10,000 neuron friends, all talking and listening simultaneously. While exactly how these networks work remains a big mystery, we know that they function through coordinated electrical activity, like a huge biological computer.

NEURONS AND SYNAPSES

Neurons are tiny cells in the brain that generate electrical signals and communicate through synapses—small structures where messages travel from one neuron to another.

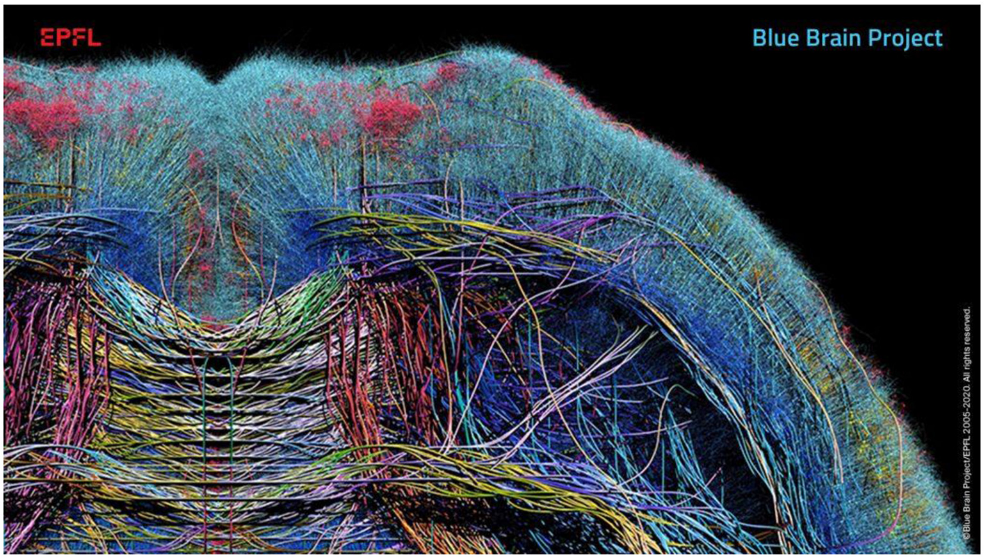

Figure 1

Figure 1

A computer-generated image of a real neuronal network in a mouse brain. The magenta-blueish tree-like patterns, neatly organized into columns, represent the brain's neurons, while the colored lines (blue, red, yellow) depict the fibers connecting neurons within the network (Figure credit: Blue Brain Project; see more here).

NEURONAL NETWORK

A system of interconnected neurons that communicate with each other. A neuronal network can include just a few neurons or up to many millions.

Science has made significant progress in understanding the brain, but many questions remain unanswered. We still do not fully understand even simple things, such as how we make smooth, controlled movements and how we recognize objects we see. We know little about how the brain generates the creativity we express through thoughts, language, and art.

One exciting theory suggests that neural networks learn to predict how actions impact our sensations and generate perceptions. We shall call this the theory of **action-perception loops** and propose that this theory explains how our brains efficiently learn new skills, including imaginary experiences we have never had. For example, have you ever experienced floating or flying in your dreams? These dreams might originate from the brain's ability to invent imaginary links between actions and sensations. The same theory of action-perception loops helped scientists develop new brain-computer links, as described in this article.

ACTION-PERCEPTION LOOP

A continuous loop where actions influence perception, and perception, in turn, influences subsequent actions (see more here).

BRAIN-COMPUTER INTERFACES

The idea of a "bionic man" first appeared in science fiction (most of us know about the six-million-dollar man). Over time, these science-fiction ideas have become closer to reality. In the 21st century, scientists developed technology to read the brain's electrical signals and connect it to a computer. This groundbreaking technology, which allows the brain and a computer to communicate and understand each other, is called "Brain Machine **Interface**", or BCI [1]. It offers hope for revolutionary clinical applications, leading to medical advances that could help people with certain conditions, like paralysis, overcome brain malfunctions. BCIs aim to train the brain to integrate machine-like devices into its action-perception loops, making those devices feel like a natural part of the body. There are different types of BCIs, and we focus on two: one that controls arm and hand movements, and another that converts brain signals into typed or spoken output words.

INTERFACE

An interface is what you use to interact with something else, like the buttons on a tablet or the screen on a phone, so you can tell it what to do.

BCI FOR CONTROLLING ARM MOVEMENT

Suppose you want to drink chocolate milk at breakfast. Achieving this seemingly simple goal requires the brain to perform a series of complex computations involving sensations and actions, such as determining how far the cup is from your mouth, calculating how to activate the muscles to reach for it, lifting the cup, and drinking without spilling the milk. We learn these skills from childhood, through practice. At first, the coordination required to drink a cup of milk involves effort (just see how a 1-year-old child copes with drinking from a cup). Eventually, it becomes effortless because we have practiced it so many times. The same principle applies to other brain functions, such as writing, drawing, and speaking. We learn to perform these complex functions smoothly, even under variable conditions. For instance, we can write with a pen on a sheet of paper and with a marker on a whiteboard equally easily. Try it, you may notice that your typical handwriting remains consistent between these two very different tasks.

Now, imagine what happens when a person is paralyzed due to a spinal cord injury. The brain can plan movements, but it cannot activate the muscles because it is disconnected from the arms. In other words, the person cannot turn their thoughts into actions. This is where the BCI comes in to help! The first BCI technology, developed ∼30 years ago, enabled patients with paralysis to control a **prosthetic** arm (Figure 2) [2, 3]. In this **neural prosthesis**, the computer translated the electrical activity from the brain's neuronal networks into the motion of the robotic arm. The paralyzed person thinks, "I want to eat the chocolate bar that I see in front of me", and the computer (fed by the brain's signals) commands the robotic prosthesis to bring the chocolate bar to the person's mouth (see here).

A PROSTHESIS OR PROSTHETIC

Describes an artificial device that replaces a missing body part.

NEURAL PROSTHESIS

A prosthetic device operated with neuronal signals or neuronal electrical stimulations.

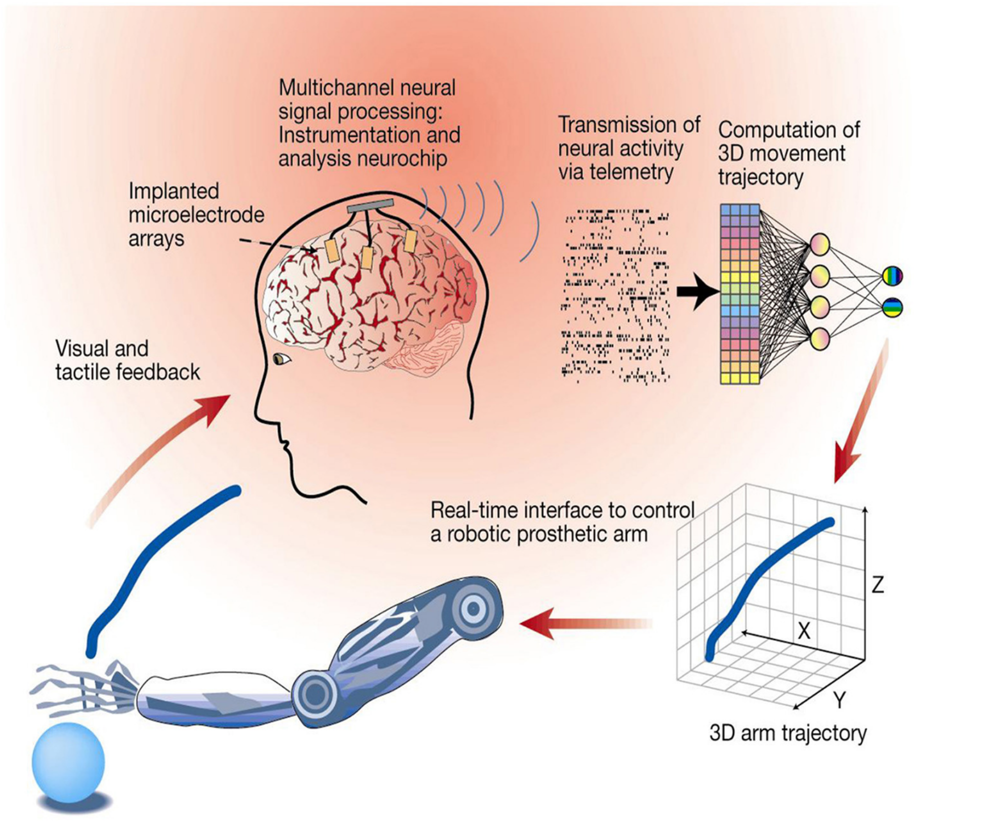

Figure 2

Figure 2

How a BCI works. A person with paralysis sees a blue ball. The electrodes implanted in the person's brain record signals from many neurons and transmit them to a computer. The computer then interprets these signals and sends a command to a robotic arm. Finally, the actual motion of the robotic arm is fed back to the person as sensory feedback, showing the movement trajectory of the robotic arm (Figure adapted from Nicolelis [2]).

BCI FOR WRITING AND SPEAKING

In 2021, new BCIs were developed that could translate thoughts into actions in new, exciting ways. These BCIs can read a person's neuronal activity while they are thinking about a sentence, and can then display the sentence on a screen for the person (and others) to read (Figure 3) [4]. This is exciting because this type of BCI could enable people who are paralyzed to communicate their thoughts to others (see here). More recently, the same scientists created a BCI through which the computer could *speak* based on a person's thoughts [5]! Another group added a cool twist to the idea by having the computer show an avatar of a woman talking (see here).

EMBODIMENT

Embodiment means that our bodies and minds are connected, and our physical experiences help us learn, feel, and interact with the world around us. In this paper, we argue that BCI can attribute a personal nature to something nonhuman (for example, a prosthetic arm).

BCI CAN TEACH US ABOUT HOW THE BRAIN WORKS

The exciting progress in the field of BCIs can also help researchers understand how the brain coordinates complex behaviors, including perception, thoughts, and imagination, through the activity of neurons. BCI experiments demonstrated directly that action-perception loops are adapted by altering the connectivity in the brain's neuronal networks. This phenomenon raised new ideas about **embodiment**, in which the brain learns to adopt prosthetic devices and other

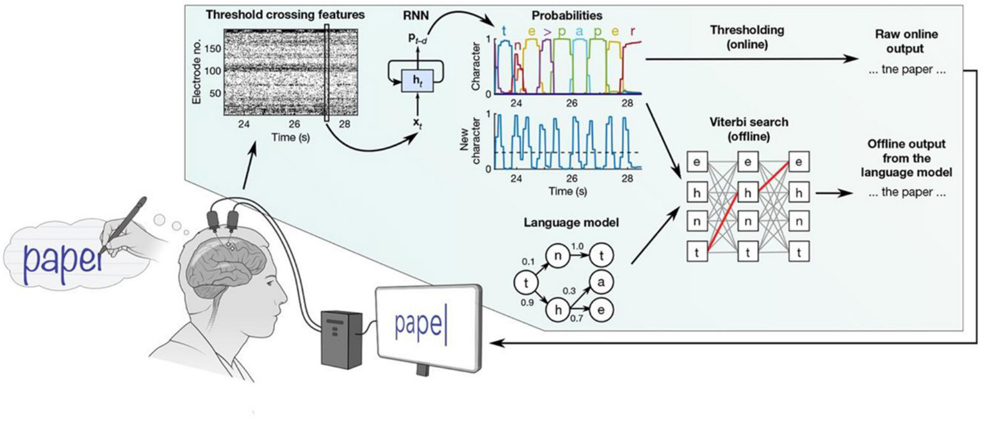

Figure 3

Figure 3

BCI to help people speak. Neuronal signals (spikes, marked here as "threshold crossings") are recorded from the brain and transferred to a computer that interprets the activity. The computer goes through several stages of computing and produces text on the computer screen (adapted from Willett et al. [4]).

machines as part of the body. Interesting evidence for embodiment was illustrated by an interview with a woman who uses a BCI to move her prosthetic arm. She said, "It was hard getting there, but now (after learning) I simply think as if I am moving my own hand".

THE FUTURE OF BCI

BCIs provide modern scientific and medical benefits, helping people recover lost brain functions. Although significant progress has been made over the past 30 years, BCIs still require improvements in several areas. Technologies like **artificial intelligence**. and **deep learning** are sure to enhance BCIs. Another crucial breakthrough for BCIs is the development of new methods for recording the activity of thousands of neurons without damaging brain tissue.

In summary, brain-computer interfaces are already transforming lives by restoring lost abilities and offering new ways to communicate. As the technology improves, BCIs may also help us unlock deeper secrets of how the brain works, opening the door to future breakthroughs in medicine, neuroscience, and human imagination.

ARTIFICIAL INTELLIGENCE

Hardware and software systems that can learn, reason, perceive, make decisions, solve problems, and control machines like robots (see more here).

DEEP LEARNING

A way computers learn by using many layers of connected units, like a brain does, to recognize patterns, make decisions, or understand things like speech and images (see more here).

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YOUNG REVIEWERS

TOBY, AGE: 13

I am a 13 year old boy originally from Australia. I love sport, chess, and technology.

AUTHORS

EILON VAADIA

Eilon Vaadia was born in 1945 and joined the Hebrew University in 1966. In 2009, he became the founding director of the Edmond and Lily Safra Center for Brain Sciences (ELSC). He is now a professor emeritus and the father of three daughters and seven grandchildren. The Vaadia lab has developed and studied Brain-Computer Interfaces to understand how the brain learns, remembers, and controls behavior. Recent advances in BCIs have led to a new understanding of the brain in health and disease, paving the way for innovative clinical solutions for brain disorders. *eilon.vaadia@mail.huji.ac.il