Brain-machine interfaces: assistive, thought-controlled devices

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A brain-machine interface (BMI) is a system for rapid reading and decoding of brain activity that allows an individual to operate a machine or computer interface with their thoughts alone. Occasionally touted as 'mind reading', this technique has the potential to restore movement to paralyzed individuals, and recent experiments in monkeys and humans are already demonstrating the clinical impact of BMI technology.

The Brain-Machine Interface

Millions of people in the world are afflicted with disorders of the motor system¹. Amyotrophic Lateral Sclerosis (ALS), stroke, and spinal cord injuries are a few impairments that leave patients unable to effectively move or interact physically with their environments, despite otherwise intact brains. By re-routing signals from the brain directly into machines, bypassing damaged spinal cords or peripheral motor neurons, BMIs can restore the ability for paralyzed patients to directly interact with and manipulate their environment. A BMI receives neural signals from a patient's brain, typically from surgically-implanted electrodes. The system then decodes and sends these signals into a computer or assistive device, allowing the patient to control the device solely with brain activity (Fig. 1)². When successful, BMIs have the potential to greatly improve the quality of life for patients with motor impairments.

Science of the brain-machine interface

Macaque monkeys are the primary model system for testing BMI devices. Humphrey and colleagues³, who performed some of the earliest work, found that activity of neurons in motor cortex of monkeys' brains

could provide fairly accurate predictions of arm motions made by the animals. This neuronal 'tuning' is the crux of BMI systems: individual brain cells in motor cortex can represent individual motor actions. For example, a neuron may respond well when the monkey moves its arm upwards. Meanwhile, another neuron may respond well when the monkey turns its wrist or grasps with its hand. By recording from many of these neurons, and applying training and decoding algorithms on the activity, researchers can then make 'best guesses' of what the animal is intending to do simply by observing these neural responses. The BMI system automatically performs this exact task, but it is also attached to a machine or computer that can then convert the animal's intended motion into motion of a robotic arm or cursor on a computer screen. The ideal result is an external device that is fully controllable by brain activity.

Testing the BMI

Testing of these systems in monkeys is complicated: electrodes must be implanted, and the animal must then learn to perform tasks for reward by only using its own brain activity. This neural activity must also be read out and decoded rapidly by a computer employing the experimenter's algorithms. Some of the simple, earliest BMIs involved monkeys learning to adjust neuronal firing rates to move cursors on displays of LEDs⁴. Subsequent research has used much faster computers and more sophisticated decoding algorithms, along with behavioral tasks more akin to what could be applied to humans⁵.

In one impressive example, the Schwartz lab developed a BMI that connected macaque monkeys to a robotic arm⁶. Without use of their own arms, the monkeys learned to use brain activity to guide the robotic arm to bring marshmallow

FIGURE 1 | Intracortical sensor and placement, participant 1. (a) The BrainGate sensor (arrowhead), resting on a US penny, connected by a 13-cm ribbon cable to the percutaneous Ti pedestal (arrow), which is secured to the skull. Neural signals are recorded while the pedestal is connected to the remainder of the BrainGate system (seen in d). (b) Scanning electron micrograph of the 100-electrode sensor, 96 of which are available for neural recording. Individual electrodes are 1-mm long and spaced 400 μ m apart, in a 10 x 10 grid. (c) Pre-operative axial T1-weighted MRI of the brain of participant 1. The arm/hand 'knob' of the right precentral gyrus (red arrow) corresponds to the approximate location of the sensor implant site. A scaled projection of the 4 x 4-mm array onto the precentral knob is outlined in red. (d) The first participant in the BrainGate trial (MN). He is sitting in a wheelchair, mechanically ventilated through a tracheostomy. The grey box (arrow) connected to the percutaneous pedestal contains amplifier and signal conditioning hardware; cabling brings the amplified neural signals to computers sitting beside the participant. He is looking at the monitor, directing the neural cursor towards the orange square in this 16-target 'grid' task. A technician appears (A.H.C.) behind the participant. From Hochberg, L.R. et al. *Nature* 442, 164–171 (2006).

treats to their mouths. In another recent study, monkeys were trained to operate robotic wheelchairs via wireless BMI

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FIGURE 2 | Overview of monkeys using BMI to control wheelchair. (a) The mobile robotic wheelchair, which seats a monkey, was moved from one of the three starting locations (dashed circles) to a grape dispenser. The wireless recording system records the spiking activities from the monkey's head stage, and sends the activities to the wireless receiver to decode the wheelchair movement. (b) Schematic of the brain regions from which we recorded units tuned to either velocity or steering. Red dots correspond to units in M1, blue from PMd and green from the somatosensory cortex. (c) Three video frames show Monkey K drive toward the grape dispenser. The right panel shows the average driving trajectories (dark blue) from the three different starting locations (green circle) to the grape dispenser (red circle). The light blue ellipses are the standard deviation of the trajectories. From Rajangam, S. *et al. Sci. Rep.* **6**, 22170 (2016).

devices (Fig. 2)⁷. Using their neural activity as a control signal, the monkeys learned to drive the chairs and navigate towards fruit rewards. These applications highlight the ultimate goal of the BMI field, which is to bring the devices to human patients

who, despite having complete brain faculties, have severely impaired motor abilities.

Translation to human patients

One of the first demonstrations of a functional implanted BMI system in humans

was in 2006, when a 96-channel electrode array was placed in the brain of a 25 year-old quadriplegic man². Researchers implanted the electrodes into a region of the primary motor cortex that represented arm motion, and recorded from neurons that modulated their activity when the patient imagined moving his arm, wrist, or hands. Then, the scientists recorded this neural activity while the patient imagined moving a cursor on a computer screen. With the aid of computers for rapidly analyzing this data, the BMI system could successfully predict, with some accuracy, where the patient was intending to move this cursor. Because the system was connected between the patient's brain and the computer, the quadriplegic patient was able to control this 'neural cursor' on the computer screen and perform simple tasks like opening emails.

In another trial, two different quadriplegic individuals were implanted with a similar system and connected to a robotic arm⁸. After the neural decoder was calibrated, the patients could successfully control the robotic arm using their brain activity. In one demonstration, a patient reached for and grasped a bottle of coffee, then brought it to her mouth to drink, the first time she had done so in 14 years.

There have been several such trials performed in humans and some studies that are currently ongoing, which leaves many neuroscientists, doctors, and patients hopeful about the future of assistive BMI devices.

Challenges to overcome

Despite the strides that have been made in BMI research, there are several complications that hinder progress. These systems currently rely on expensive robotic equipment, computers, large teams of scientists, and involve invasive neurosurgery to implant the recording electrodes. Furthermore, BMIs require sophisticated filtering and decoding algorithms, and even then do not afford their users perfect control over computer cursors or robotic arms. Other assistive devices already exist, such as pupil-tracking and blink- or muscle-activated systems, which offer writing and speaking ability to their users. Thus, current implantable BMI devices are not the most efficient or economic option for patients with motor impairments.

However, many scientists are hopeful to overcome these limitations, given time and funding. Many paralysis-inducing disorders such as ALS, spinal cord injury, and locked-in syndrome, leave human patients with complete mental abilities but without the capacity to move their own bodies. If neural activity could be safely and easily used to control devices, then these patients could experience a greatly improved quality of life.

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