1

Introduction

Our brains evolved to control a complex biological device: our body. As we are finding out today, many millennia of evolutionary tinkering has made the brain a surprisingly versatile and adaptive system, to the extent that it can learn to control devices that are radically different from our body. Brain-computer interfacing, the subject of this book, is a new interdisciplinary field that seeks to explore this idea by leveraging recent advances in neuroscience, signal processing, machine learning, and information technology.

The idea of brains controlling devices other than biological bodies has long been a staple of science-fiction novels and Hollywood movies. However, this idea is fast becoming a reality: in the past decade, rats have been trained to control the delivery of a reward to their mouths, monkeys have moved robotic arms, and humans have controlled cursors and robots, all directly through brain activity.

What aspects of neuroscience research have made these advances possible? What are the techniques in computing and machine learning that are allowing brains to control machines? What is the current state-of-the-art in brain-computer interfaces (BCIs)? What limitations still need to be overcome to make BCIs more commonplace and useful for day-to-day use? What are the ethical, moral, and societal implications of BCIs? These are some of the questions that this book addresses.

The origins of BCI can be traced to work in the 1960s by Delgado (1969) and Fetz (1969). Delgado developed an implantable chip (which he called a "stimoceiver") that could be used to both stimulate the brain by radio and send electrical signals of brain activity by telemetry, allowing the subject to move about freely. In a now-famous demonstration, Delgado used the stimoceiver to stop a charging bull in its tracks by pressing a remote-control button that delivered electrical stimulation to the caudate nucleus in the basal ganglia region of the bull's brain. At around the same time, Fetz showed that monkeys can control the activity of single brain cells to control a meter needle and obtain food rewards (see Section 7.1.1). Slightly later, Vidal (1973) explored the use of scalp-recorded brain signals in humans to implement a simple noninvasive BCI based on "visually evoked potentials" (Section

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6.2.4). The more recent surge of interest in BCIs can be attributed to a confluence of factors: faster and cheaper computers, advances in our knowledge of how the brain processes sensory information and produces motor output, greater availability of devices for recording brain signals, and more powerful signal processing and machine-learning algorithms.

The primary motivation for building BCIs today is their potential for restoring lost sensory and motor function. Examples include sensory prosthetic devices such as the cochlear implant for the deaf (Section 10.1.1) and retinal implant for the blind (Section 10.1.2). Other implants have been developed for deep brain stimulation (DBS) to treat the symptoms of debilitating diseases such as Parkinson's (Section 10.2.1). A parallel line of research has explored how signals from the brain could be used to control prosthetic devices such as prosthetic arms or legs for amputees and patients with spinal-cord injuries (e.g., Section 7.2.1), cursors and word spellers for communication by locked-in patients suffering from diseases such as ALS (amyotrophic lateral sclerosis) or stroke (Sections 7.2.3 and 9.1.4), and wheelchairs for paralyzed individuals (Section 12.1.6). More recently, researchers have begun exploring BCIs for able-bodied individuals for a host of applications (Chapter 12), ranging from gaming and entertainment to robotic avatars, biometric identification, and education. Whether BCIs will eventually become as commonplace as current human accessories for sensory and motor augmentation, such as cellular phones and automobiles, remains to be seen. Besides technological hurdles, there are a number of moral and ethical challenges that we as a society will need to address (Chapter 13).

The goal of this book is to serve as an introduction to the field of brain-computer interfacing. Figure 1.1 illustrates the components of a generic BCI. The aim is to translate brain activity into control commands for devices and/or stimulate the brain to provide sensory feedback or restore neurological function. One or more of the following processing stages are typically involved:

1. **Brain recording**: Signals from the brain are recorded using either invasive or noninvasive recording techniques.
2. **Signal processing**: Raw signals are preprocessed after acquisition (e.g., by bandpass filtering) and techniques for artifact reduction and feature extraction are used.
3. **Pattern recognition and machine learning**: This stage generates a control signal based on patterns in the input, typically using machine-learning techniques.
4. **Sensory feedback**: The control signal from the BCI causes a change in the environment (e.g., movement of a prosthetic arm or a wheelchair, change in the grip of a prosthetic hand). Some of these changes can be seen, heard, or felt by the user but in general, one can use sensors in the environment such as tactile sensors, force sensors, cameras, and microphones, and use the information from these sensors to provide direct feedback to the brain via stimulation.

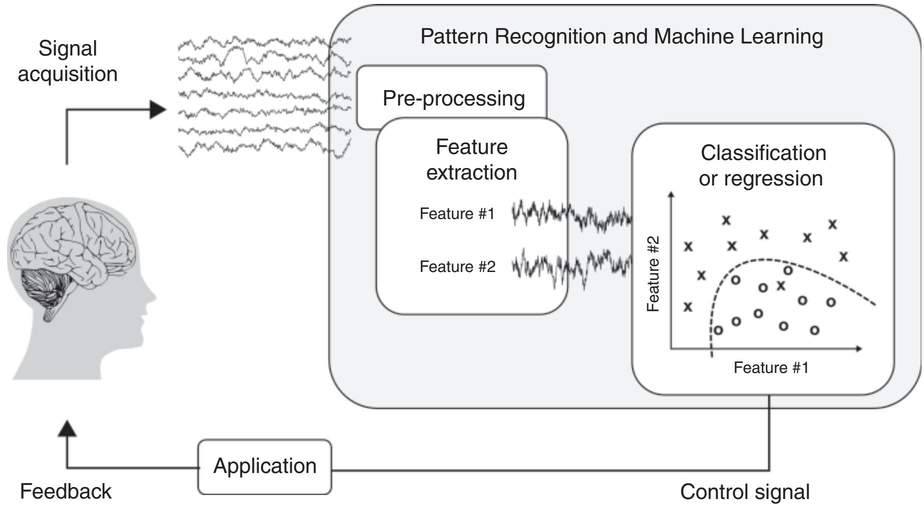

Figure 1.1. **Basic components of a brain-computer interface (BCI).** (Adapted from Rao and Scherer, 2010).

5. **Signal processing for stimulation**: Before stimulating a particular brain region, it is important to synthesize an activity pattern for stimulation that mimics the type of activity normally seen in the brain region and that will have the desired effect. This requires a good understanding of the brain area being stimulated and the use of signal processing (and potentially machine learning) to home in on the right stimulation patterns.
6. **Brain stimulation**: The stimulation pattern received from the signal processing component (5) is used in conjunction with invasive or noninvasive stimulation techniques to stimulate the brain.

It is clear from the stages of processing listed above that to begin building BCIs, one must have a background in at least four essential areas: basic neuroscience, brain recording and stimulating technologies, elementary signal processing, and basic machine-learning techniques. Often, beginners in BCI come with a background in one of these areas but usually not all of them. We therefore begin our journey into the world of BCIs with Part I (Background), which introduces the reader to basic concepts and methods in these four areas.

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