# The science of neural interfaces

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## Summary

Over the last century, neuroscience has made considerable progress in understanding how the nervous system controls behaviour.

Scientific advances have been enabled by neural interface technologies used for stimulation and recording in animals. These reveal how information is represented and processed by neural circuits in the brain and spinal cord.

Now the application of similar technologies in humans offers new opportunities to treat injury and disease.

## Neurostimulation

The nervous system is an interconnected network of many billions of cells called neurons. Neurons communicate by sending electrical impulses known as action potentials. Electrical current applied to parts of the nervous system causes nearby neurons to transmit action potentials to their targets.

Early neuroscientists used electrical stimulation in animals to map how the nervous system was connected to the body. They found that stimulation of some nerves generated twitches in the limbs while other structures could elicit sensations such as sounds. Today neurostimulation can help paralysed people to move[1], and can restore lost senses such as hearing.

In other cases, electrical stimulation disrupts the signals being conveyed by nearby neurons. This is thought to underlie therapeutic uses of spinal cord stimulation for pain relief, and deep brain stimulation for Parkinson’s disease.

Repeated stimulation can also change the strength of connections between neurons, through a mechanism known as neuroplasticity. Neuroplasticity is thought to underlie learning and memory. Neurostimulation techniques that manipulate neuroplasticity have been shown to improve rehabilitation following a stroke.

The brain influences other organs in the body through the autonomic nervous system. In future, neurostimulation may allow therapeutic control of organs to treat disease[2].

Since neurostimulation can be delivered selectively to specific parts of the nervous system as and when required, it may be more effective and have fewer side-effects than pharmaceutical treatments.

## Stimulation interfaces

Electrodes implanted within the body provide the most selective neurostimulation. However this requires complex surgery and risks damaging delicate neural structures.

Neural structures can also be stimulated with electrical current passed through the skin, but this less selective and can also be painful. Consequently, other nonimplantable neurostimulation methods are being developed. These include transcranial magnetic stimulation, focussed ultrasound and high-frequency electrical fields that can be directed beneath the skin towards deeper parts of the brain or spinal cord.

In recent years, both implanted and non-implanted modes of stimulation have been applied to the same neural structures for treatment of the same neurological disorders (eg to the vagal nerve for cluster headache, the occipital nerve for migraine, the tibial nerve for overactive bladder and the hypoglossal nerve for obstructive sleep apnea). The trade-offs between these stimulation modes include:

1. selectivity in the activation of neural structures, ranging from sub-millimetre to several centimetres and higher for implanted interfaces resulting in better efficacy, tolerability and safety, once surgical implantation has been successfully achieved;
2. level of patient compliance, which is higher for implanted interfaces;
3. acceptance of the therapy by patients and physicians - higher for non-implanted interfaces due to avoiding surgical risks;
4. marketing strategy: physician-focused for implanted and physician plus consumer-focused for non-implanted.

The nervous system contains different types of cells, for example excitatory and inhibitory neurons. In recent years, it has become possible to control specific types of neurons using gene therapies to render them sensitive to light (optogenetics), ultrasound (sonogenetics) or magnetic fields (magnetogenetics). These techniques present exciting new therapeutic opportunities, but the long-term risks of such genetic manipulations have yet to be determined.

**Neural recording**

Modern neuroscience has developed many different techniques for monitoring the activity of neurons. These techniques have been used to explore the neural mechanisms of sensory, motor and cognitive functions.

By understanding how brain activity relates to behaviour, it is becoming possible to decode thoughts and intentions from the brain. Thus brain-machine interfaces have enabled paralysed individuals to control assistive devices such as computers, wheelchairs and prosthetic limbs[3].

Many neurological conditions are associated with abnormal brain activity. This can be recorded by neural interfaces and relayed as vital diagnostic information in real-time. For example a neural interface might be used to detect and warn a patient of an impending seizure.

**Recording interfaces**

By implanting electrodes inside the nervous system it is possible to detect action potentials transmitted by individual neurons. Arrays of electrodes can now monitor hundreds of neurons simultaneously. However, stable recording from implanted electrodes over long periods of time remains a challenge.

Field potentials arise from the combined activity of many neurons and can thus be detected outside the body using electroencephalography (EEG) or magnetoencephalography (MEG). MEG offers greater spatiotemporal resolution than EEG, but requires magnetically-shielded environments. At present, neither EEG nor MEG offer the same spatial resolution as implanted electrodes.

Haemodynamic techniques infer brain activity from associated changes in blood flow and therefore have limited temporal resolution. While functional magnetic resonance imaging (fMRI) requires bulky equipment, functional near infrared spectroscopy (fNIRS) detects haemodynamic signals using wearable optical sensors. At present, fNIRS can only reach superficial brain structures, but improved techniques may in future provide images from deeper in the brain.

All of these techniques yield large quantities of data, requiring sophisticated analysis methods. Increasingly, machine learning techniques are being used to help interpret and decode brain signals.

## Bidirectional interfaces

New therapeutic opportunities are presented by neural interfaces that combine recording and stimulation capabilities. 'Closed-loop' neurostimulation is adjusted according to the current state of the nervous system as monitored by recording technologies and may therefore be more effective than 'open-loop' neurostimulation[4]. For example, devices can detect the onset of an epileptic seizure and deliver appropriate stimulation only when required.

Bidirectional interfaces can also relay information from one part of the nervous system to another. This allows artificial connections to replace damaged nerve pathways, for example from the brain to the spinal cord[1]. In future, bidirectional interfaces may also be able to replace or augment the functions of damaged brain areas.

Bidirectional interfaces that provide sensory feedback to the user may allow more natural control of brain-machine interfaces[3].

## Conclusions

Neural interface technologies underpin neuroscientific research, which in turn drives new therapeutic applications.

Neural interfaces can replace, modulate and augment the functional parts of the nervous system that have been damaged by neurological injury or disease. Brain-machine interfaces allow paralysed users to communicate and control assistive devices.

Neural interfaces can also offer targeted, specific and selective delivery of therapy to other organs in the body controlled by the autonomic nervous system.

## References

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