Chapter 4

Neuronal Interface Systems

Part of the challenge faced by anyone seeking to seriously examine the ethical implications of applying neuro-based technology to cyber-based aspects of life is the pace of change of such technology. But it is also important to distinguish between what is fact and what is science fiction, or what on occasions is more a matter of future-fiction, given that the ideas are so incredible that they are unlikely to ever become reality.

Indeed, it is difficult not to be sceptical concerning the grand vision of greatly enhanced human cognitive abilities and the use of neuronal interface systems that have sometimes been presented. In addition, the suggestion that laptop computers are already more intelligent than insects needs to be qualified, since simply comparing neurons to computer capacity is inappropriate. As already mentioned, unfortunate comparisons have been portrayed between biological brains and computers. Moreover, the choice of analogies and language may reflect the implicit values and worldviews of the persons making such claims.

The way in which the neuronal system works is far more complex and efficient than silicon-based systems. In biological systems, the basic functioning unit is molecular or cellular. This is in contrast to electrons moving along a wire or in a semi-conductor. If connectivity is also taken into account, the brain is extremely intricate, with each neuron having direct connections with up to thousands of other neurons. Furthermore, the brain operates as a network based on interactions from external impulses, which means that if an activity is not maintained, it will slowly disappear.[1]

Over the past few years, however, new developments in information technology and a better understanding about how the human brain functions has enabled new ways in which communication interfaces between the brain and appliances, such as computers, can be considered.

Developments in Information Technology

When pictures of Apollo 11 were presented showing that humans had landed on the moon in 1969, the world held its breath and stood in awe as humanity congratulated itself on its technological brilliance. Human beings were amazed at what they could do in partnership with the technological world. The guidance system, in particular, could solve equations at unparalleled speed, with the processor being capable of performing around one million calculations a second. Using this, a millennia-old fantasy to go into space could be achieved.

At present, however, the numbers seem to come on a different scale. A standard laptop computer now performs billions of calculations a second and this is increasing annually. This means that developments in the way in which neuronal interfaces may find new applications, such as with ever more powerful computers, will also likely increase.

Moore's Law

By mapping out the progress in raw computing power onto a chart, it is possible to observe a phenomenon known as Moore's Law (though it is an observation and not a law). In 1965, the cofounder of the computer company *Intel Corporation*, American Gordon Moore, predicted that computing power would double about every two years. He also suggested that: 'Integrated circuits will lead to such wonders as home computers – or at least terminals connected to a central computer – automatic controls for automobiles, and personal portable communications equipment.'[2] Over the following decades, this predicted exponential growth appears to have been respected. The cost to the consumer has also plummeted on a similar basis.

Currently there seems to be no break in the trend, though there are signs that this line may not simply stretch out indefinitely. As companies have increased the technical functions that can be squeezed into a computer chip, development costs of each new aliquot of functionality has increased accordingly. Initially, it was relatively easy to double the power – now developments seem to be approaching the buffers as the components within a chip become atom-sized elements. A probable limit could be reached between 2020 and

2040, though this may be cirumvented in new forms of computers. For example, research teams are already examining whether it may be possible to harness living neurons as a means of packing more information into a very small space.

The Internet

Another development that has taken place in parallel to the expansion of computers is the Internet, which is a network of networks formed of private, public, academic, business and government computers linked by a broad array of electronic, wireless and optical technologies. The Internet supports an extensive range of information resources and services, such as the applications of the World Wide Web, which is an information space where documents and other web resources can be identified, interlinked and accessed.

The Internet was originally developed through research commissioned by the U.S. government in the 1960s with the aim of building strong, fault-tolerant communication via computer networks. The subsequent interconnection of regional academic systems in the 1980s then marked the beginning of the transition to what is now known as the Internet. This grew exponentially when numerous institutional, personal and mobile computers were connected to the network from the early 1990s onwards.

The advent of the Internet and the World Wide Web have made computers much more useful than they could ever have been on their own. In developed countries, nearly every home, office, school and shop can reach out to pools of knowledge or share documents in a near-instantaneous fashion.

Developments in Understanding the Brain

In recent years, a lot more effort has also gone into understanding the manner in which the brain works, with several large-scale research endeavours being initiated. These include the already mentioned BRAIN initiative, which was launched by U.S. President Obama in 2013 to 'accelerate the development and application of new technologies that will enable researchers to produce dynamic pictures of the brain that show how individual brain cells and complex neural circuits interact at the speed of thought'.[3]

It is suggested that this, and other similar initiatives, will show how individual cells and complex neural circuits interact in both time and space, enabling new solutions to be considered to treat, cure and even prevent brain disorders. They will also provide unprecedented opportunities for exploring and understanding how the brain enables the human body to record, process, use, store and retrieve information.[4]

Another related project is the Human Brain Project supported by the European Union, which began in 2013. This represented a substantial scientific endeavour aiming at building a collaborative infrastructure allowing researchers across the globe to advance knowledge in the fields of neuroscience, computing and brain-related medicine.[5]

However, more complex philosophical questions will remain with respect to consciousness and the nature of the mind. For example, even though a better biological understanding of the brain is developing, questions remain as to whether this will ever improve the philosophical or legal understanding of what it means to be conscious or to be a moral agent.[6]

Developments in Neuronal Interfaces

Developments in neurotechnology are encouraging the brain to expand its physical control beyond the limitations of the human body. In this way, it is possible for information to be obtained from brains and for information to be provided to brains, and for feedback mechanisms to be set up in which the thoughts of a person can influence the workings of a computer or the reverse.

In this regard, one of the first to use neuronal implants was a Swiss ophthalmologist and scientist, Walter Rudolf Hess (1881–1973), who received the Nobel Prize in 1949 for mapping different areas of the brain. From the 1920s onwards, he experimented with cats, to which he implanted, while anesthetised, very fine wires into their brains. When awake, he then stimulated these wires using weak electrical current to examine their reactions.[7]

A few years later, in the early 1950s, the U.S. psychiatrist Robert Galbraith Heath (1915–99) was the first researcher to implant electrodes deep into living human brains of patients with very severe mental disorders. The patients often experienced remarkable and positive changes of moods and personalities using the stimulated electrodes.[8]

Following on from such developments, the very possibility of neuronal interfaces including devices that enable an interaction between a neuronal network and a system, such as a mechanical machine or computer, as well as a possible direct association between the mind and cyberspace, has encouraged many new ideas in futurology. This has included the prospect of 'jacking into' cyberspace or being able to upload a person's mind into a computer.

In many ways, neuronal interface systems are already in use, but many different kinds and levels of sophistication exist for such devices. Some applications, for instance, are more practical and realistic, which may assist disabled persons in recovering some of their lost functions, such as the use of their limbs. Indeed, a significant amount of work is already taking place in seeking to address motor function and sensory organs.

In the future, the use of neuronal interface systems using a computer may even improve a person's cognitive functions, such as memory, reasoning speed or access to data. But caution and realism is necessary to avoid overstating or exaggerating possible uses. Visionary proposals of bioelectronic neurocomputers and microelectronic neuroprostheses (an artificial device replacing a missing part of the brain) will not be possible in the near future, if at all, because of practical limitations.

Moreover, such interventions are not without risks, especially when invasive procedures that modify the very structure of the neuronal network are considered. Because of this, research projects using invasive systems are only considered when very serious limitations are experienced by the person. In these situations, modifications may be suggested to the brain that would otherwise be considered unethical.[9]

In the following sections, a sort of state-of-the-art presentation will be given as to what is already possible in relation to neuronal interface systems in which human neuronal networks, including the brain, can be directly associated with electronic technologies such as computers. Future prospects will then be examined, as well as the consequences that this may have on possible interfaces between the mind and cyberspace.

Procedures Involved in Neuronal Interfaces

Neuroscience has evolved over the past few decades to enable the development of new interfaces between elements in the outside world, including machines and computers, which can stimulate or record activities in the human nervous system. For instance, human brain–computer interfaces are now becoming useful tools in the development of neuroscience, bringing new insights into:

- the neuronal basis of brain function;
- neuronal coding and representation;
- brain behaviour and perception;
- the neurobiological basis of certain diseases.

In order for a useful neuronal interface to be considered for a broad range of neuroscience applications, it must be able to analyse and/or stimulate specific areas of the brain for particular time periods, while addressing concerns relating to safety, usability, reliability, patient acceptance and cost.

In this regard, a number of technologies are already being developed or considered that can be used to analyse or modify certain areas of the brain over a long period of time, such as through the use of wireless technologies. Moreover, the development of a better understanding of 'background' brain activity is allowing greater control of the information coming in and out of the brain.[10]

At the moment, neuronal interfaces have generally relied on visual feedback in which a person looks at the activity produced by the interface in order to decide how best it can be controlled and used, but new forms of sensory feedback systems may become possible in the future.

Considerable interest has also been expressed for neuronal interfaces that record and process brain activity in real time through implanted electrodes. It may then be possible for the brain to learn how to incorporate this activity into normal function. These neuronal interfaces could, for example, be applied to directly control a patient's paralysed muscles. Indeed, such interfaces are already being used to directly stimulate the muscles in the body of disabled persons, while receiving feedback from the network of neurons responsible for the sense of balance or movement in these persons' brains.[11]

Applications that may prove more ethically challenging in the future are those that involve long-term modifications to the strength of connections between the neurons that are associated with learning and behaviour. In this regard, neuronal interfaces could actually modify the brain to react in a certain manner to a certain kind of stimulus in order to enhance the learning process.

Progress in the development of neuronal interfaces could also affect higher-order areas of the brain to produce what can be characterised as cognitive replacement parts, causing significant changes in terms of how the brain operates and functions. These could be considered, for example, to address the consequences of a stroke in a patient, but could, in addition, be used to manipulate and even exploit others.[12]

The technology is also enabling new uses to be considered that not only seek to restore a function, but enable human beings to be enhanced in some way or access completely new experiences. For instance, it may in the future be possible to extend neuronal interface applications to new forms of brain manipulation aimed at cognitive enhancement or neuronal 'modification' or 'correction'.

In relation to these future possibilities, three types of neuronal interface systems are generally considered: [13]

1. Interfacing out (output) of the nervous system: this enables biological information to exit a neuronal network, such as the brain, which can then

be sent to some form of computer that interprets the signal and triggers events or actions. For example, it enables brain information to be read and used in controlling a limb.

2. Interfacing into (input) a nervous system: this inputs information into a living neuronal network from outside, such as from a computer. For example, it enables a cochlear implant to provide sound information into the brain.
3. Interfaces made of feedback loop systems: these interpret information from a living neuronal network and sends it to an external processor, which then returns information back into the neuronal network.

At this stage, it should also be emphasised that, because it is difficult to see into the future, it is impossible to predict which technologies may become relevant in the development of neuronal interfaces and the resulting association of the mind with cyberspace. Therefore, the following list of neuronal interface systems is merely a summary of what is already beginning to exist in order to present what may eventually be possible.

Output Neuronal Interface Systems: Reading the Brain and Mind

The brain is often said to be similar in consistency to cold porridge, with the skull offering a huge degree of protection in normal life; however, it also keeps the brain out of reach from any form of simple observation. Because of this, and as already discussed, it was only at the beginning of the nineteenth century that biologists, such as the Frenchman Jean-Pierre Flourens, began to understand that different functions could generally be ascribed to particular regions of the brain, though a finer localisation was a lot more difficult.

Yet, as a result of Italian physician, physicist and philosopher Luigi Galvani's (1737–98) discovery that nerves and muscles were electrically excitable, Flourens and the Italian anatomist Luigi Rolando (1773–1831) were able to begin examining how parts of the brain could be electrically stimulated. This revealed further information about what areas corresponded to which function.

The first serious mapping of the brain started in the early 1800s, with scholars such as the German neuroanatomist Franz Joseph Gall (1758–1828) publishing in 1805 his *Lehre von den Verrichtungen des Gehirns* (*Lessons on the Activities of the Brain*). In this, he correctly proposed that different parts of the brain generally had different functions, but incorrectly suggested that these functions could be studied by examining the exterior of a person's skull. The concept became known as phrenology.

In actual fact, in order to determine what is happening inside a brain, it was necessary to measure the electrical signals that are present in a neuron or group of neurons. Historical research in this area dates back to the 1950s, with the examination of squid neurons, which are exceptionally large and easy to manipulate. The final aim was to obtain a complete read-out of the state of a brain by measuring every single electrical signal in every brain neuron.[14]

At present, neuronal output interfaces that can be used to analyse brain functions are very much anticipated by scientists. The aim is for electrical signals from the brain to be interpreted in order to predict cognitive intentions, such as performing a movement, meaning that they could eventually replace any lost connections that a person's brain has with his or her body or any other machine. Nonetheless, neuronal interfaces could eventually become the preferred way for human beings to interact with computers instead of using keyboards, touchscreens, mice and voice command devices.[15]

Interfacing out of the brain with output neuronal interface systems can take place, first of all, though the means of electrodes that can either be situated on the surface of the skin of the head (noninvasive) or inside the skull (invasive). The different types of electrodes used result in significant differences in success rates in terms of making contact with the desired area or cell type in the brain. Safety concerns also vary depending on which kinds of electrodes are used or where they are located. For example, surgery is required with implanted and invasive electrodes, which is associated with a number of risks.

Another more general and indirect read-out of brain activity can be obtained through different kinds of scanning procedures. These do not directly measure the electrical activity of neurons, either individually or in groups, but rely on the fact that thinking necessitates small amounts of energy that can be measured in terms of the variation of brain metabolism. But this still has many limitations and can only be used for some of the most basic brain activities.[16]

Invasive Output Neuronal Interface Systems

The first experiments using invasive neuronal interfaces with electrodes placed inside the brain were undertaken on nonhuman primates, such as Rhesus monkeys, in the 1970s in the United States.[17] From these experiments, a relationship was discovered between the electrical responses in the brains of these monkeys and the direction in which they moved their arms.[18] More recently, experiments using electrode implants in the brains of the same species of monkeys have been undertaken to associate brain signals with their use of a mechanical robotic arm. [19]

Research on invasive output neuronal interface systems is now increasingly being considered to provide new functionality to certain disabled persons. In this regard, one of the first experiments took place in the year 2000 whereby a number of electrodes were implanted into the brain of an individual who had suffered a stroke, resulting in paralysis. This enabled the patient to learn to move a cursor on a computer screen by thinking about various hand movements.[20]

By and large, the best resolutions obtained from brain signals with humans involve the implantation, through surgery, of very small electrodes directly into the brain of an individual at a depth of about 1.5–3 mm. This enables the recording of signals from very small groups of neurons giving the greatest level of control.[21] But since functions in the brain are not usually associated with a single group of neurons, it is often necessary to consider a more general picture of the brain using a number of electrodes.[22] However, it should be noted that such invasive neuronal interfaces are prone to scar-tissue build-up, which may cause the signals to become weaker, or even non-existent, as the body reacts over time to the foreign device in the brain.

Partially Invasive Output Neuronal Interface Systems

Some neuronal interface systems are less invasive and can analyse brain signals on the surface of the brain but inside the skull. In this case, because there is no forced penetration of the brain, less damage is inflicted to the cerebral cortex.[23] But in these partially invasive systems, the electrodes are still positioned through surgery with the associated risk of infection.

Recordings through partially invasive systems may provide a better spatial resolution than those recorded on the scalp and may enable greater stability than recordings taking place inside the brain. However, their resolution usually remains inferior to more invasive neuronal interfaces and, so far, only limited investigations have been undertaken on humans.[24]

Noninvasive Output Neuronal Interface Systems

Noninvasive output neuronal interface systems usually analyse brain activity through the use of neuroimaging, including the application of electrodes on the surface of the head rather than through direct implantation inside the skull. This makes surgery unnecessary and avoids the associated risks of neuronal damage and infection. In this way, a kind of image of what is happening in the brain is examined. Clinical applications for human disorders are progressing only slowly. These include neuronal interfaces used to analyse movement intentions for patients who are paralysed.[25] They can also be considered for patients who are not able to express themselves, such as locked-in patients, who retain cognitive functions but cannot move or communicate verbally due to complete paralysis of nearly all voluntary muscles in the body.

As a result of developments in the medical field, other applications are now being considered, such as in the gaming industry. Examples of games that use noninvasive neuronal interfaces include those where participants wear headsets while trying to control, through their thinking, the motion of a small ball on a screen. The headset measures brain activity by way of multiple electrodes placed on the outside of a person's skull, while using brain sensors linked to wireless technology to control the ball.[26]

Neuroimaging

The term 'neuroimaging' refers to a group of noninvasive technologies that acquire measurements of the brain's structure, biochemistry or function without having to physically investigate the brain. They generally measure the architecture and activity of large populations of neurons and usually interpret signals from many locations throughout the entire brain simultaneously.

The procedures presented below differ in terms of their: (1) spatial resolution (how well they can distinguish between two close points in the brain); and (2) temporal resolution (how well they can distinguish between two close moments in time). Unfortunately, there is often a trade-off between these two forms of resolution, though this can often be addressed by using a combination of procedures.[27]

Neuroimaging techniques can also be classified into two broad categories, namely 'structural' (or anatomical) neuroimaging, which observes the brain's architecture, and 'functional' neuroimaging, which examines images that reflect the brain's activity.[28]

X-Rays

One way to look inside the skull of a human being is through X-ray photography. This originated with German physicist Wilhelm Roentgen's (1845–1923) discovery of high-energy particles in 1895 and his realisation that they could pass through solid objects leaving a shadow-like image on a fluorescent screen. Indeed, his observation that the beam of particles only reflected the bones of his wife's hand launched a whole industry.[29]

The images are useful in determining the shape and structure of hard materials in the human body, such as bones and kidney stones. But when the rays pass through soft materials, such as the brain, only a small effect is noticed. Thus, on their own, X-rays have little to offer the brain scientist or neurologist.

Computed Tomography (CT)

Adding computers to X-rays enabled more information to be obtained, since X-rays can come in many different power settings showing up different kinds of soft tissue. Thus, a Computed Tomography (CT) scanner can take thousands of horizontal brain images, in sections, using varying levels of X-rays that can then be used by a computer to build up these fragments of information to create a picture. With enough scans, it is even possible to create a three-dimensional image of the whole brain.

The first clinical CT scan on a patient took place in 1971 in England.[30] The patient had a suspected frontal lobe tumour and the scanner produced an image with a sufficient amount of detail to see the growth. Since then, image quality has improved and CT has become a valuable clinical tool. For example, it is used in many hospitals throughout the world to immediately assess the results of a stroke or head injury, since it has the ability to quickly detect bleeding within the skull. Moreover, CT scans can be used to look for brain tumours in a person or to better evaluate, in more detail, abnormalities seen in normal X-rays. However, it is worth noting that for research and increasingly many clinical purposes, CT has now generally been replaced by Magnetic Resonance Imaging (MRI).

Positron Emission Tomography (PET)

Positron Emission Tomography (PET) scans were developed in the 1970s and have revolutionised the understanding of how the brain works. The procedure requires a patient to lie in a scanner, while radio-labelled trace particles, such as a radioactive form of oxygen, are injected into the blood to be used as markers. The scanner then detects the radioactivity of the tracer molecules, thereby creating real-time images of the concentration of these tracers in different parts of the body.

When it is used to look at the brain, PET may reveal which areas are most active while a person performs specific tasks. For example, it is possible to ask a person to imagine doing nothing or playing tennis. The computer can then compare the two sets of images, making it possible to distinguish an increase in radioactivity in a particular area that is related to the blood flow changes resulting from brain activity. In other words, the rise in radioactivity in a certain region indicates that the brain is working harder and calling in more oxygen. While such assumptions are probably correct, a difficulty exists in that it is usually a whole area of the brain that 'lights up'. PET scans can therefore provide information about general function, but give little or nothing in the way of fine detail.

Magnetic Resonance Imaging (MRI)

It was in 1980 that, for the first time, a UK team used a Magnetic Resonance Imaging (MRI) machine to obtain a clinically useful image of a patient's internal tissues. This identified a primary tumour in the patient's chest, an abnormal liver and secondary cancer in his bones.[31]

An MRI scanner consists of a large cylinder containing an extremely powerful magnet. When a patient lies inside the scanner, a magnetic field is then created, causing changes in the magnetic properties of atoms in the body, which are subsequently analysed through a computer in order to produce images. These include pictures of organs, soft tissues, bone and virtually all other internal body structures. One of the advantages of MRI is that the different elements of a brain structure can be given different contrasts, enabling a detailed anatomical structure to be visualised.

Detailed magnetic resonance images are now the most sensitive imaging test of the head and brain in routine clinical practice. They can indicate if there are any changes in shape caused by a tumour, stroke or injury and can also be employed to investigate neurological disorders such as Alzheimer's disease and epilepsy.[32] However, MRI cannot show anything about the cell-level functioning of any of the brain areas.

Functional MRI (fMRI)

The most widely used extension of MRI to detect aspects of neuronal activity in the brain is called functional Magnetic Resonance Imaging (fMRI), which uses Blood Oxygenation Level Dependent (BOLD) imaging. This measures changes in the oxygenation level of the blood and indicates which areas of the brain are most active at any given time. These variations arise because neurons consume oxygen when they are active, which leads to compensatory changes in local blood flow to the active area.

Usually, fMRI is used while a participant performs certain tasks, enabling researchers to associate brain activity with sensory, motor or cognitive processes. But it is important to emphasise that BOLD measures neuronal activity indirectly through measuring changes in blood oxygenation levels. Since blood flow takes place several seconds after neuronal firing, this limits the temporal resolution of fMRI, meaning that although the image is detailed, it is impossible to observe rapid changes in activity.

Typically, fMRI is combined with a rapid production of brain data, giving a continuous series of images of the brain – one every few seconds over a period of about 40 minutes – while the participant performs particular tasks. This enables an examination of the nature of brain processes with respect to brain activity.[33]

It should be noted that fMRI has now largely supplanted PET for providing dynamic images of brain activation because it is an entirely noninvasive recording of neuronal activity across the entire brain with relatively high spatial resolution (range of millimetres) and moderate temporal resolution (range of seconds).[34]

However, caution should be shown when interpreting the statistical probability of results obtained from fMRI, especially in cognitive examinations, since a significant amount of fMRI research on emotion, personality and social cognition may be using unreliable procedures.[35]

Electroencephalogram (EEG) and Magnetoencephalography (MEG)

Ever since the German psychiatrist Hans Berger (1873–1941) invented the electroencephalography (EEG) in 1924 by attaching multiple electrodes to the outside scalp of a head, a form of direct communication between the brain and an external device has become possible.

A similar procedure called magnetoencephalography (MEG), in which sensors replace the electrodes on the head to record naturally occurring magnetic fields produced by electrical currents in the brain, was then developed.

In this regard, measurements are now usually collected by placing up to one hundred electrodes or sensors on the person's head using a wet gel to improve contact with the skin.[36] These are sometimes attached individually or built into a cap.

EEG detects the very small synchronised electrical activity of many hundreds of thousands of neurons, whereas MEG detects the very small changes in magnetic fields associated with the electrical activity of these large groups of neurons. These results enable the production of a 'map' of human brain activity second by second associated with thought processes directly and noninvasively.

However, the spatial resolution of EEG and MEG is limited because of the difficulty in measuring electrical or magnetic signals deep within the brain and the intrinsic complexity of trying to correspond signals on the scalp with activity in specific brain areas. But EEG can still be used, for example, to detect general patterns of electrical activity resulting from thought processes or the brain waves that occur during sleep. When a person is asleep, his or her brain goes through a number of cycles of activity. Initially he or she will be in a light sleep and the surface electrodes will record small amplitude high frequency waves. As a person moves into a deeper phase of sleep, the waves increase in amplitude and decrease in frequency. It is then possible to see specific patterns associated with dreaming.

Indeed, when individuals wake up from a deep sleep, their brainwave frequencies will increase through the different specific stages of brainwave activity. During the waking cycle, it is possible for individuals to stay in the mixed state of activity for 5–15 minutes, whereby their brain is running through a free flow of ideas about previous events or contemplating the coming day's activities. It can be an extremely productive time filled with meaningful and creative mental activity.

Another advantage of EEG is that the electrodes are readily available and portable, making it far easier to use than other methods. Moreover, since EEG and MEG provide a measure of brain activity that directly reflects the electrical activity of neurons, in contrast to the indirect signals related to blood flow measurements obtained from fMRI and PET, which have a better spatial but worse temporal resolution, they are often used in cooperation.

Though EEG does not involve as many risks as more invasive procedures, it does have some disadvantages. For instance, muscle contractions in the face or other electrical appliances may interfere with the recording of electrical signals in the brain. Some training is also required for a person to appropriately use the technology and interpret the results.[37]

Near-Infrared Spectroscopy (NIRS)

Near-infrared spectroscopy (NIRS) is a noninvasive procedure enabling the absorption of light at near-infrared wavelengths to be measured. By applying such a light source and array of detectors to the intact skull of a person, a measurement of how much light is transmitted can be examined. This is especially used with infants who have relatively thin skulls and in combination with other imaging procedures. However, NIRS has a relatively low spatial resolution because of the difficulty in seeking to localise scattered light through a skull and the limited penetration of infrared light into a brain.[38]

Other Output Systems

Other interventions exist enabling a significant amount of information to be gathered from the brain, including the exact position of all the neurons and their interactions, but these cannot be considered as interface systems since they would require the individual to have died. However, because some of them are already being suggested in the very improbable context of mind uploading (which will be considered in a later section), these will now be briefly presented.

Light Microscopy

Light microscopy has developed quite significantly in the last few decades. Automated systems can now even slice, represent and analyse entire brains from dead mice in a day, generating a considerable amount of useful information. More advanced systems are capable of creating three-dimensional models of mouse brains that take about a week to prepare.

The importance of these procedures is significant when combined with careful staining systems. In this way, it is possible to place a stain in one zone of the brain and then, after a fixed amount of time, to kill the animal in order to study in which parts the dye has diffused. Adding different types of dyes under different circumstances to different parts of the brain enables neuroscientists to build a massive three-dimensional map or catalogue of all the neuronal connections. By the time the data from thousands of mice is added (each one being killed in the process), it is possible to obtain a fascinating overview of life inside a mouse brain.[39]

Doing this for a human brain is theoretically possible, but there are some insurmountable obstacles: first, it requires a number of brains from deceased persons so that they can be cut into slices; second, it requires that appropriate dyes be added to specific parts of their brains just before these persons die; and, third, it requires massively scaled-up machines that provide a very large amount of data.

The resolution of these systems is very good, but it is only possible to determine where neurological cells begin and end, without knowing very much about the final terminals, the intercell communication systems (the synapses). This lack of knowledge significantly restricts any understanding of what is really going on at each nerve ending.

Electron Microscopy (EM)

With electron microscopy (EM), which requires the brain to be dead, frozen, sliced and stained, it is possible to observe the very small junctions between the neurons. EM generates very good images of these complex junctions, providing a detailed understanding of the structure of small volumes. However, it is not feasible to scale this up to the level of a mouse brain, let alone a human.

Input Neuronal Interface Systems: Changing the Brain and Mind

As already mentioned, scientists such as the Italian Luigi Rolando started to electrically stimulate parts of nonhuman animal brains back in the eighteenth century, while examining whether these were similar to those found in humans. This eventually resulted in clinical applications, with input neuronal interfaces providing stimulation to specific parts of the neuronal network in seeking to restore or improve function.[40] These are technologies that take signals from the outside and provide it to an individual's neuronal system. Again, they can be classified as invasive and noninvasive procedures.

Invasive Input Neuronal Interface Systems

Neuronal Implants for Deafness

A number of different technologies have been, and are continuing to be, developed over the years to address the diminished, or complete lack of, hearing function in certain individuals. These have revolutionised the options offered to person who want to regain a better (or even just some) form of hearing. These include: (1) cochlear implants that bypass the dysfunctional signal recognition system in the ear; and (2) auditory brain stem implants that completely sidestep the whole hearing system.

Cochlear Implants

Cochlear implants have revolutionised the lives of many individuals who were either born with no ability to hear or became deaf after birth. In a healthy hearing system, pressure waves in the air (defined as sound) enter the outer ear and make the tightly stretched fragile membrane, the ear drum, vibrate. A set of three very small bones in what is called the middle ear on the inner side of the eardrum pick up this vibration and mechanically amplify the signal. The last bone in the sequence makes contact with a spiral structure that resembles the outside of a snail shell. Known as the cochlear, this is filled with fluid and lined with millions of hair-like projections. The vibrating bones cause pressure waves to travel through the liquid, thereby deflecting the hairs. In turn, this deflection sets off an electrical impulse that travels along the auditory nerve to an area of the brain known as the auditory cortex.

A cochlear implant is used when hearing loss is caused by anything that prevents a signal entering the auditory nerve, but when this nerve remains intact and functional, such as when severe damage exists to the outer or middle ear, or when the hair cells in the cochlear have been lost.

The system works by clipping a set of about twenty very small pin-like electrodes around the auditory nerve so that the pins come into contact with the auditory nerve bundle and make close connections with the nerve fibres. A short cable is then connected between the electrodes and a sound microprocessor, containing microphones, which is normally positioned on the outside of the skull behind the user's ear so that it picks up sound in a similar way to a healthy human ear. In this way, the sound gathered by the microphone is turned into coded signals by the external processor (which selectively filters sound to prioritise audible speech), which is then transmitted to the implanted unit that converts them into a set of signals sent to the twenty different electrodes.

Accordingly, a cochlear implant works very differently from a conventional hearing aid. Instead of simply boosting the sound and blasting it to the eardrum, the implants generate signals that are sent straight to the auditory nerve. In this way, they bypass the physical mechanism that pick up sound in normally hearing people, while, at the same time, circumventing many of the problems that may develop in people who have difficulties in hearing. For first-time users, the response is instantaneous. Even people who have been deaf from birth have an immediate sensation that they may equate with sound, though quite what they are hearing is difficult to determine.

The auditory nerve has about 30,000 axons (all associated with their respective neurons), which would normally be linked to individual hair cells. This accounts for a human being's faculty to distinguish between very small differences in tone, as well as his or her ability to detect multiple frequencies all at once. However, with a cochlear implant, the entire bundle is stimulated by just twenty pins. Consequently, much of the detail will be lost. If the person was deaf since birth, another layer of uncertainty may exist, in that his or her auditory brain cortex will never have received a signal and will be untrained.

The first neuronal implants have been remarkable, but current research is driven by a need to find new ways of making hundreds or thousands of connections with the auditory nerve, while making sure that those connections are stable. Currently, the twenty electrodes just sit within the nerve bundle and if they move a little, then it does not make too much difference. They were never located to a specific axon. However, if the number of connections goes up, then it will be important for movement to be reduced. Given that axons are fractions of a millimetre in size, the smallest movement could cause the electrode to move relative to the axon.

Auditory Brainstem Implants

A further step in the treatment of people with severe hearing loss is to bypass not only the outer, middle and inner ear, but also the auditory nerve itself. This is at an earlier stage of development, but neuronal interface implants, consisting of an array of very small electrode needles, have already been positioned directly into the auditory area of the brainstem of patients.

The process requires surgery into the skull that is far more invasive than just placing the electrode on the cochlear nerve.

At the moment, such implants are not as good at conveying sound as when cochlear nerve implants are used, but they can help a previously totally deaf person become more aware of everyday sounds. However, it can take months for the hearing area of the brain to learn to use this new input. At first, patients describe the sound as indefinite noises, but over time users can pick up a sensation of pitch and loudness.

The device has already been implanted into several thousands of adults and, in 2013, the U.S. Food and Drug Administration approved a clinical trial for children in America.[41] A few devices have also been implanted in children in Europe.

A 2012 study of brainstem auditory implants concluded that most people who received them developed functional hearing, with awareness and recognition of environmental sounds. It also enabled some to enhance their lip-reading skills, while a number acquired enough speech recognition to conduct telephone conversations.[42] But some patients still go through the trauma of surgery while receiving very little (if any) benefit from the devices.

There is also an active debate about whether these implants should be offered to more children. On the positive side, the auditory system continues to be developed over the first decade of life. Fitting a device during that period would increase the brain's likelihood of adapting to its signals. Research demonstrates that the brain is particularly malleable before the age of two. This means that the implants may be particularly powerful if put into very young children.[43]

On the other hand, positioning the electrode is accomplished by destroying the cochlear. This means that it is a once-in-a-lifetime decision when the device is installed and rules out any other technology that could be developed in the future. This can be particularly pertinent when considering such an implant for a young child, given the pace of progress. It may well be that a far superior device may become available long before he or she reaches adulthood. In addition, it is uncertain how the implant will respond as the child develops, since there is a risk that the interface may be pulled out of place over time.

Future Developments with Neuronal Interfaces for Hearing

Using a phone is currently hard for some people with hearing implants because the sound from the phone's loudspeaker has to be picked up by the microphone and then processed. Therefore, it has been suggested that a mobile phone capability be built directly into the implant, enabling the person to be hardwired into the phone system. In order to overcome any risks of having a microwave transmitter so close to the brain, it may also be possible to send the signal using a pocket-held transmitter. In addition, wireless interfaces are being considered that would reduce the need for communication wires.

Interestingly, there would be no need to limit the input to phone calls. This sort of device could, theoretically, let a person listen to radio and watch television with the volume on mute. In addition, there is no reason why the microphone should be limited to picking up sounds in the normally audible range. Bats navigate by emitting high-frequency sounds and picking up the echoes, so it may be feasible in the future to build a similar system into implanted devices. In theory, a person could then switch to night operation and turn their hearing system into a navigational radar.

Resistance from the Deaf Community

It would be easy to assume that everyone who cannot hear will be excited by these developments and would welcome the possibility of implants. But this is not the case. Without the ability to hear, deaf people have developed various forms of sign languages and, just as with different spoken languages in different parts of the worlds, a strong culture has developed amongst deaf persons in which signing is a critical element.

Individuals are brought together by their need to sign and this gathering brings a distinct identity. People in these communities use the capital D deliberately saying they are Deaf, in the same way that others would say they are French or German. This means that an implant that removes deafness may be considered as a highly disruptive technology and could be seen by some as unwelcome. The strength of feeling is such that, on occasions, Deaf parents whose condition is the result of having particular genes have argued to be allowed to use embryo screening to choose Deaf offspring. Their desire is to have a child who can join in with their community rather than be part of a 'foreign' social identity.[44]

Retinal Vision Implants

Vision implants are also being considered to treat non-congenital (acquired) blindness. In this regard, a very limited visual sensation has been possible with retinal implants in which a digital camera is worn by the user that transmits an image, through an electrical signal, to an electrode array implanted on the back of the retina of his or her eye. This gives some general perception, but a number of limitations still remain, including biocompatibility problems.

One of the first researchers to study the possibility of using neuronal interface systems to restore sight was undertaken by the British physiologist Giles Brindley in 1968, who implanted an 80 electrode device on the visual cortical surface of a 52-year-old blind woman. As a result, she was able to recognise some directly induced patterns.[45]

Further experiments were developed by the American biomedical scientist William Dobelle (1941–2004). In 2000 he indicated that he had used cameras mounted on glasses to send signals through a computer to a 68 array of very small electrodes implanted into a blind person's visual cortex, which succeeded in producing the sensation of seeing light.[46]

Future Developments with Neuronal Interfaces for Vision
Further developments are now being considered that use more sophisticated implants, such as wireless interfaces, enabling better and more coherent vision. However, in order for good images to be obtained on the retina, a large number of very small electrodes would be necessary, enabling an important amount of information to be received without creating a lot of heat that would otherwise damage the surrounding tissue. Moreover, in a similar manner to auditory interfaces, implants that are directly linked to the visual cortex are now being examined.

Interestingly, if progress continues to develop with this technology, it may be possible for a person to distinguish the near-infrared region, which would be of great value in night driving.[47] In fact, research published in 2013 has already demonstrated how sensitivity to infrared light can be developed in rats through the use of implanted devices.[48] In addition, just as with hearing neuronal interfaces, it may be possible in the future to hardwire a person directly into the output of a video machine so that the person will 'see' pictures sent directly by a computer.

Deep Brain Stimulation (DBS)

Deep brain stimulation (DBS) was initially developed in France in the late 1980s. It involves employing long needles, which can be manufactured with multiple electrodes on either their tip and/or their length. Using image-guided surgery, these are carefully pushed deep into the brain of a person to the position where it is believed the neurons are malfunctioning. In an attempt to address this functional deficit, pulses of electric current are then sent down to the affected region, resulting in a possible dramatic and positive effect on symptoms.[49]

Interestingly, what actually happens at the end of the electrodes remains unclear, but it is likely that the creation of a small current between the electrodes excites the neurons in the surrounding area and modifies communication between them.[50] DBS has also been shown to initiate very real and important, metabolic and neurochemical brain changes when continual stimulation takes place.[51]

Applications of Deep Brain Stimulation
In the past few decades, DBS has increasingly been considered as a treatment option for certain serious disorders. It has even been shown that placing electrodes in specific brain areas reduces tremor and rigidity in patients affected by Parkinson's disease, increasing their ability to move and walk. In other situations, the procedure has been used to control chronic pain, epilepsy, migraine, depression, Alzheimer's disease and obesity, with variable reports of improvement.[52]

However, with DBS, there is always a risk of damaging blood vessels in the brain or disturbing previously healthy regions as the electrodes are inserted. This means that the procedure can only be used in patients with severe symptoms that cannot be controlled by pharmaceutical treatments.[53]

DBS electrodes can also be connected via a subcutaneous extension wire to battery-driven stimulus generators that may be implanted subcutaneously so that the system is located entirely within the patient's body.[54] But it is important to note that even though DBS is an intervention that may increase the patient's quality of life, which is otherwise restricted by his or her illness, it is neither life-saving nor curative.[55]

From a more research-based perspective, DBS offers the ability to study specific and important brain functions and cognitive abilities while considering them in real time. For instance, it is possible to examine the effects of DBS on agency and decision-making because the procedure can directly change a person's mood and behaviour by modifying the biological neuronal basis of unconscious and conscious mental states. This can be done either intentionally, if the individual was affected by a major psychiatric indication such as a serious depressive disorder, or as an unintended consequence of the procedure that was undertaken for another reason.[56] On this account, the European Parliament's 2009 Science and Technology Options Assessment's report entitled *Human Enhancement Study* indicated:

> [A] presupposition underlying much of the debates on the societal and ethical implications of technologies such as DBS is that they manifest that medicine has come to grips with something that was until recently considered to be out of reach of direct medical intervention: the mind . . . The capacity of turning on and off emotions, moods, motor control . . ., simply by switching on or off one's DBS, appears to powerfully illustrate this enlarged power of science and technology.[57]

In this regard, the fact that DBS may have a direct, unconscious effect on a patient may give rise to questions about his or her ability to make free will decisions, since it in unclear whether it is the patient or the DBS device that is actually in control of his or her different moods and their consequences. For example, if the depressive symptoms of certain patients can only be addressed by DBS, then they may be uncertain whether they are, in fact, in complete control of their behaviour and thoughts. However, control is very likely to be a matter of degrees depending on the manner in which DBS may affect different persons.[58]

It is also possible to examine the way in which patients' experience with DBS can affect their concepts of identity and how it alters their sense of who they are, whether or not they are even aware that this change has occurred. Indeed, the influence of DBS on identity is unique in that:[59]

1. DBS is an implantable system that is foreign to the brain and that can be switched on and off – in this respect, the device can be used to study changes to the sense of identity of a person;
2. there may be a difference between the identity change noted by the patient and the persons in contact with him or her – this is because the patient may still consider that he or she is the same person, while others may believe he or she has become a different person.

Therefore, serious questions are still being asked about the use of DBS in certain circumstances.[60] But this has not stopped new possible, non-clinical neuro-enhancing applications of the procedure to be considered, though further investigations relating to its efficacy and ethics would be necessary.[61]

This all means that ethical and legal questions with DBS are very real. These include questions surrounding the context of autonomy, accountability as well as liability, and whether it should be possible to use DBS for non-medical reasons.[62]

Fibre-Optic Cable Light-Sensitive Neurons

Another new, though still very much experimental, procedure enabling scientists to study brain functions uses genetically engineered neurons in rodents, which are light-sensitive. When these are then exposed to blue light delivered by a fibre-optic cable, the neurons are triggered to transmit a signal to cells downstream in the neural circuit. Thus, by making specific groups of neurons fire at will, it is possible to study specific connections in the brains of the rodents.[63] However, no applications of this technology are, as yet, being considered for human beings.

Noninvasive Input Neuronal Interface Systems

Transcranial Brain Stimulation (TBS)

Though some forms of brain stimulation such as electroconvulsive therapy (ECT), in which seizures are electrically induced in patients when seeking to provide relief from psychiatric disorders, have been used since the 1930s, these will not be discussed in the following study since they do not have any further applications in neuronal interfaces.

But one group of appliances that is increasingly being considered is Transcranial Brain Stimulation (TBS). This refers to a set of noninvasive applications that stimulate the brain either by inducing an electrical field using a magnetic coil placed against the head in transcranial magnetic stimulation (TMS) or by applying weak electrical currents via electrodes on the scalp with transcranial direct current stimulation (TDCS) and transcranial alternating current stimulation (TACS).

The principle of electromagnetic stimulation underlying TBS is that electrical currents can be created to selectively activate certain parts of the brain, producing particular outcomes by affecting large volumes of neurons. They are generally considered in research since TMS and TDCS can be used to both suppress as well as stimulate neuronal activity. They are thus particularly useful when combined with purely observational neuroimaging techniques, since the procedures can examine whether the activity of neurons in a specific brain area is necessary or causal for a certain brain function.[64] TBS can also be used to understand the functioning of the brain by tracking networks and pathways.

The ability to modify brain activity raises the question whether TBS procedures may, in addition, be able to deliberately change brain functions and, as a consequence, modify thoughts or behaviour. Interestingly, some of these procedures are already being used in clinical settings, such as in trying to address drug-resistant depression or treat other psychiatric and learning disorders, though the exact mechanisms of their therapeutic effects are still being researched.[65] But already 10,000 adults have undergone such stimulation, which seems to be safe in the short term.[66]

Transcranial Magnetic Stimulation (TMS)

Transcranial magnetic stimulation (TMS) has been used by scientists since the mid 1980s, especially in studies examining motor control. The procedure involves placing a coil of wire (enclosed in plastic) near the scalp over the brain area to be stimulated and then delivering a pulse of large current lasting less than one millisecond. This produces a magnetic field, creating weak electrical currents inside the brain through electromagnetic induction. As a result, the thousands or millions of neurons in the area below the coil are briefly stimulated, in a nonspecific fashion, to a depth of approximately 3.5 cm into the skull, thereby affecting cognition or motor function.

As such, TMS may be used as a diagnostic tool as well as in research, where it is employed, for example, to examine how the pulses alter the amount of time it takes for a person to recognise a face, add numbers or complete sentences.[67,]

In 2008, the U.S. Food and Drug Administration approved TMS to treat migraine and refractory depression in adults,[68] and there are no known long-term effects, though there is a very small risk of initiating an epileptic seizure during stimulation.[69] The procedure is also increasingly being considered to address a number of psychiatric and neurological disorders such as mania, obsessive-compulsive disorders, schizophrenia and Parkinson's disease.[70] At the same time, there is some evidence that TMS could be used for cognitive enhancement for healthy individuals, including improving cognitive skills, moods and social cognition.[71]

However, one of the challenges with TMS is that the stimulation effects are generally only temporary. Difficulties also exist with directing the magnetic pulses to a specific area in the brain that is responsible for a certain function without activating other areas as well.[72]

Transcranial Direct Current Stimulation (TDCS) and Transcranial Alternating Current Stimulation (TACS)

The noninvasive stimulation of the brain through the use of electrical currents is not new. Ever since the beginning of the twentieth century, it has been possible to apply electrodes to the scalp of a person, enabling an electric current to be created in the brain.[73]

With TDCS, a weak electric field is applied to the scalp (using noninvasive electrodes) in the region of interest, thereby inducing intracerebral current flow leading to alteration of brain function. In a research setting, measurements can then be obtained through the study of small reaction time changes in behavioural performance on psychological tasks.[74]

Recent studies in stroke rehabilitation strategies have shown that TDCS may improve a patient's ability to learn a simple coordination exercise, with improvement remaining three months after the end of the experiment. Studies are also taking place with the aim of treating depression and the effects of Parkinson's disease.[75]

In addition, it has been suggested that the procedure could be used to enhance the cognitive ability of healthy people by improving working memory, word association and complex problem-solving.[76] For example, in 2016, the U.S. military reported that TDCS could improve skill learning and performances, such as multitasking of air crew and other military personnel.[77] Other studies have suggested that several sessions of TDCS applied to the prefrontal cortex improved the moods of some individuals for several weeks[78] or made people less likely to take risks.[79]

In this regard, although devices prescribed for medical treatments must meet specific safety standards, there is currently no legislation in Europe or the United States regulating the use of TDCS for persons who simply hope to enhance certain aspects of their cognition. TDCS headsets can even be purchased online, enabling them to be used (even on children) without taking into account the eventual risks.[80]

With TACS, the procedure is similar to TDCS, but alternating current is used instead of a direct current. This causes the underlying neurons of the brain to oscillate at specific frequencies.

Feedback Systems of the Brain and Mind

In the previous sections, output interfaces were considered that involved communication technologies that externalise information from the brain. Input interfaces were then examined, enabling signals taken from the outside to be internalised into the brain of an individual. These are characterised as unidirectional devices.

But these two technologies can now be brought together, forming interactive feedback neuronal interface systems. These would record, for instance, the neuronal activity of a person, which would then be translated to an application that can be examined by the individual for communication and control. The person could, in other words, use the feedback to modulate neuronal activity on an ongoing basis, so that the accuracy of the intended outcome can be improved, forming, as a result, a closed loop system.[81]

In a way, such a feedback system enables the neuronal interface to be used as a kind of virtual mirror of the actual neuronal activity.[82]

Closed loop systems usually include the following stages:[83]

1. externalising brain activity (output);
2. pre-processing and making sure that background noises are addressed;
3. feature extraction that correlates brain signals to a small number of variables defined as features;
4. classification of the signals corresponding to a type of brain activity pattern;
5. translation into a command;
6. feedback in which a user is then informed of the brain activity that has been recognised.

Recording of the neuronal output activity can, of course, be achieved in a normal manner through, for example, speaking or gestures that externalise signals from the brain. But it may also take place with an output neuronal interface system that records neuronal activity and sends this information to some form of computer that makes sense of the signal and triggers events or actions.

Examination of these events or actions by the individual, enabling possible feedback, can then take place through sight (for example, watching where the external device is moving) or hearing, but also through an input neuronal interface that sends signals via a computer into the neuronal network.

In the future, it may also be possible for two or more neuronal interface systems implanted in the brain (for output and input or one that does both) to provide a direct neuronal feedback loop.

Brain Electrode-Chips

One neuronal interface system that may enable a feedback loop in a single device is a square microchip containing a number of very small hair-thin electrodes that can both read the state of certain neurons and also stimulate them (i.e. they are bidirectional devices).[84] These electrode-microchips can be implanted on the surface of the brain of an individual, through surgery, enabling the electrical activity from hundreds of neurons to be recorded from the relevant brain areas. This activity can then be translated into meaningful signals and sent to an appliance.

Such brain interfaces have already been considered in clinical trials with the aim of restoring some functionality for a limited group of severely motor-impaired individuals[85] whose thought signals are read in order to translate them into an application.

The pins of the electrode may look very slim to the human eye, but relative to the scale of neurons in the brain, they are massive. Consequently, each electrode can monitor the average activity of many hundreds of neurons, which is far beyond the more intricate level of activity in which the brain operates.

Electrodes in Capillaries

One major restriction of electrode-chips is that they only monitor the effect of large groups of neurons. This has led to a group of researchers in the United States to propose an alternative approach using the brain's extremely comprehensive network of blood vessels with capillaries that supply oxygen and nutrients to the brain's neurons. Because this reaches throughout the tissue and comes into close contact with most neurones, the scientists believe that it may be possible to feed probes through these capillaries to reach the most difficult-to-access parts of the brain with minimal disturbance.

In laboratory experiments *in vitro*, this proposal was examined using very small platinum electrodes that were successfully inserted into capillaries, which supplies oxygen through the blood, to neurons in the spinal cord. [86] Researchers now hope to further miniaturise the probe to make it steerable by employing electrically stimulated shape changes so that these very small wire-probes can be placed into the desired blood vessels and create the first true steerable nano-endoscope.

It would be an enormous technical feat if such electrodes in capillaries proved to be successful. But it is difficult to determine how they can move beyond the research stage in the near future. Indeed, in order to make connections with all the neurons in the brain, it would be necessary for billions of these very small microscopic wires to go through the estimated 25 km of capillaries that exists in a standard human brain.

Neuron-Silicon Transistors

Another approach to neuronal interface systems actually inserts an electrode into the neurone. In such a highly miniaturised and integrated device, a direct interface between neurons and silicon microelectronic systems would be developed,[87] enabling an application that could read out the electrical activity of a neuron (or even activate it in some way).[88]

It would then enable researchers to gather more information about how individual neurons work, while creating a simple memory device. However, at present, extending this system outside the laboratory would be extremely challenging.[89]

Miniature Synthetic Mesh (Neural Lace)

In 2015, scientists in China and the United States indicated that they had injected rolled-up miniature synthetic macroporous mesh (neural lace) electronics using a water-based solution in a 0.1 mm-diameter syringe into the brains of mice. This mesh, it was suggested, could then unfurl inside the mouse brain up to 30 times its size and become embedded with the living neurons.

Such a technology could enable new human neuronal interfaces to be developed, with the activities of neurons being continually monitored and manipulated through the use of microscopic sensors wired into the mesh.[90]

Interestingly, the concept of neural lace being implanted into the brains of individuals, such as young people, which then grows with them was first suggested by the Scottish author Iain M. Banks (1954–2013) in his series of science-fiction books called *The Culture*, which depicts an interstellar utopian society. In these books, the neural lace enables individuals to communicate wirelessly, including with databases, and to store their full sentience after death so that they can be re-activated. In addition, it enables all the thoughts of a person to be read, though in *The Culture*, this usually only takes place with his or her consent.[91]

Application of Feedback Neuronal Interfaces

To help pick through the complex manner in which neuronal interface systems may be used, this section will begin by considering what is already possible with respect to feedback interfaces, but will then examine future possibilities including what has crept into science-fiction films or books.

Therapeutic Applications of Feedback Neuronal Interfaces

As already indicated, by studying the relationship between brain signals, thoughts and intentions to undertake an action, brain imaging procedures may be used to externalise brain activity in a noninvasive manner. This may be useful when a person is unable to express his or her thoughts or intentions through normal channels such as speech or through certain gestures.

Neuroimaging analyses brain structures and activity in areas of the brain associated with large groups of neurons, enabling a limited kind of 'brain reading' where only a small number of thoughts or actions are considered. These have also led to an explosion of neurological investigations relating to cognitive processes in the human brain.[92]

The general aim of this research is to understand how mental processes take place in the brain and how these give rise to observable behaviour in terms of speech, thoughts, perception and motor actions or other behaviours. This can then be used to study certain brain dysfunctions associated with neurological or psychiatric disease.[93] Moreover, with MRI and PET, it is possible to localise nervous activity to within a few cubic millimetres, which is useful in terms of identifying which parts of the brain are involved in which kinds of mental activity.

Assistive Technologies

The most frequently used definition of assisted technologies was given by the U.S. Technology-Related Assistance of Individuals with Disability Act of 1988 as 'any item, piece of equipment, or product system, whether acquired commercially off the shelf, modified, or customized, that is used to increase maintain, or improve functional capabilities of individuals with disability'.[94]

In this regard, one of the first instances where neuronal feedback interfaces were considered was with patients who have a normally functioning brain, but experience dysfunction or paralysis in a certain part of their bodies. These included persons who still have a capacity for planning and imagining movement, [95] such as those suffering from spinal cord injury, stroke or amputation.[96] Accordingly, these new interfaces were developed with the aim of obtaining data from their neuronal networks and transmitting this to an appliance in order to try and restore movement or provide help with daily living.[97]

Back in 2003, the media reported the case of a former lawyer, Hans-Peter Salzmann, who had Lou Gehrig's disease, which gradually destroyed all voluntary movement.[98] His symptoms had developed to the point where his mind was described as being locked inside a paralysed body that needed a respirator to enable breathing. But he had been taught to type on his computer by controlling aspects of overall brain activity, which were picked up by two electrodes placed on the side of his scalp that were linked to a basic computer. Typing was not fast, but it gave his mind a means of escape.[99]

The first electrode-brain chips were also developed with the aim of helping people with paralysed limbs regain some function. For instance, researchers in the United States installed a brain implant in a patient named Johnny Ray (1944–2002), who suffered from 'locked-in syndrome' after suffering a brain-stem stroke in 1997. An implant was installed in 1998 and Ray lived long enough to start working with the implant. In 2000, the researchers published a study showing how he could move a cursor on a computer screen by thinking about various movements (initially movements of his hand),[100] before going on to move the cursor simply by thinking about doing so. This permitted him to carry out tasks using the computer, including writing.[101]

However, despite further work, it is still not clear how much brain chips can help 'locked-in' patients.[102] Yet there is hope that they could eventually offer novel means of communication, independent locomotion and increased control in order to improve the quality of life of these patients.[103]

Another patient, who was one of the first to use an implanted neuronal interface, was Matt Nagle (1980–2007), who had become tetraplegic after a fight in which a knife wounded his spine. In 2004, he volunteered to receive an invasive implant and became a clinical pioneer in seeking to address the very challenging difficulties of such interfaces.[104] Implanted into the area of his motor cortex that controlled arm movement, the 96-pin electrode allowed him to become the first tetraplegic person to control a robotic arm by thinking about moving his hand. Moreover, he was able to control a computer cursor, turn on lights and operate his television.[105] Since this trial, electrodes have been tested on other paralysed individuals, allowing them to control the movement of a cursor by simply imagining this motion.[106]

Further research is also taking place in private companies, such as with BrainGate™, which aims to create interface systems to help severely disabled individuals, including those with traumatic spinal cord injury and loss of limbs, to communicate and control common functions through thought processes.[107] Moreover, as progress with neuronal interface systems improves, many more applications will certainly become available with better software, generating more appropriate movements of external devices.

What is surprising in this research is that even though many years may have passed after an injury provoked paralysis, normal brain activity for movement remains present in the relevant parts of the brain that can be modulated. The same group of neurons that normally move a limb seem to remain in a person who has become paralysed and these can be used to activate an artificial device.[108]

In addition, experiments that took place in the 1960s and early 1970s in nonhuman primates demonstrated that the activity of neurons within a specific area of the brain could be directly correlated to specific aspects of movement. This was then used to enable these primates to learn feedback control of neuronal activity without actually having to move their bodies.

Interesting, basic brain patterns seem to be similar whether movement is imagined or performed, which is a useful feature in seeking to harness brain activity to operate artificial devices.[109] Moreover, since the human brain of a person can process images even before he or she may be aware of them, this could be very valuable in providing significant advantages over other systems of control in terms of speed and accuracy.[110]

The potential practical applications of feedback systems are already assisting, repairing or enhancing motor functions in many paralysed patients. Moreover, since many who have suffered some injury, such as a stroke or an amputation, retain some brain functions to generate movement intentions, these can be used to control the new limb or device or even any muscles that are still functioning. This is possible because the patient gets an idea of how well he or she is doing through the feedback mechanism. In some advanced systems, both the computer and the person 'learn' how to work together in a sort of symbiotic process.[111] For example, it may be possible for a neuronal interface to analyse certain brain signals that are associated with movement (which are generally consciously invoked, but may also be passively produced) and translate them into information that can be used to control a device in real time in a manner that reflects the intention of the person.[112]

Such feedback mechanisms enable researchers to also explore the process of learning in the human brain in the context of short-term and long-term improvements. In this regard, a very positive achievement would be for a patient with severe paralysis to regain control, communication and independence.[113]

In 2016, it was announced that three volunteers in Italy with very sever spinal injuries were able to take control of a robot in Japan through the use of EEG and a head-mounted display that showed what the robot was seeing. In order to move the robot in real time, the volunteers concentrated on special parts of the display. Moreover, to increase the feeling of control over (and embodiment in) the robot, they were provided with auditory feedback.[114]

These experiments were undertaken in the context of the European Union-supported Virtual Embodiment and Robotic Re-Embodiment Project. This aims to break down the boundary between the human and a surrogate body existing either in immersive virtual reality or in 'real' physical reality, such as with a robot body. An illusion is then created in individuals that their surrogate body is in fact their own and acting accordingly.[115] In this regard, Andy Clark explains that:

> Our sense of bodily presence is always constructed on the basis of the brain's ongoing registration of correlations. If the correlations are reliable, persistent, and supported by a robust, reliable causal chain, then the body image that is constructed on that basis is well grounded. It is well grounded regardless of whether the intervening circuitry is wholly biological or includes nonbiological components.[116]

This means, for instance, that if a person can feel and directly control an object with his or her hand, which he or she considers to be part of his or her body, then feeling and directly controlling the same object through an advanced telemanipulator may encourage this individual to similarly consider the device as being part of his or her body. This would be true even if the telemanipulator was activated at a considerable distance from the person. However, what this would then mean for the 'sense of presence' of the individual still needs to be evaluated.[117]

Similarly, the British Philosopher Jonathan Glover indicates that:

> "[I]f signals could be sent from my nervous system to receptors in physical objects detached from my body, so that I could move those objects in the same direct way I can move my arms, it might be less clear that I stop where my body ends. These doubts would be even stronger if sensory signals could be sent back, enabling me to "feel" things happening in the detached objects. We might then say that I extend beyond my body, or else we might treat these objects as free-floating parts of my body."[118]

There is also interest in using neuroimaging, such as EEG, to detect awareness in patients who are totally 'locked-in'. To do this, patients are invited to imagine moving parts of their bodies, enabling brain signals to be recorded, indicating that they are self-aware.[119] For example, it has been shown through neuroimaging that patients who were previously thought to be in a permanent vegetative state could demonstrate a sufficient level of brain function to express certain wishes. This resulted in serious discussions on whether treatment protocols for such patients should be revised to take account of their own decisions.[120] In this regard, real-time recordings would also be particularly important for engaging patients with impaired consciousness in certain activities.[121]

However, therapeutic uses of neuronal interfaces are still usually confined to clinical research in which noninvasive techniques are the most common.[122] Yet the considerable success of these trials has generated a lot of media and public interest.[123]

Neurorehabilitation

The use of neuronal interface systems is also being considered to help persons regain or relearn motor functions when these have been limited by disease or injury.[124] Such interfaces, which are usually associated with a computer, use the individual's own muscles or body part, instead of a machine, to initiate an action.

Spinal Neuronal Interface Systems

A driving impetus behind much of the work of researchers in feedback systems is the desire to find new ways of restoring movement to people whose spinal cord has been injured through an incident like a car crash or a sporting injury. In this tragic situation, a person has perfectly healthy leg muscles, with nerves running right up to and connecting with the spinal cord, but no signal reaching them. Consequently, the muscles waste away, not because they are damaged, but because they are not used.

In theory, it seems a straightforward task to build a feedback neuronal interface system that could bridge the injury and get the person walking again. First, the system would need to pick up the nerve traffic with electrodes inserted into the working end of the spinal cord. A computer would then filter the signal and detect the traffic triggered by a person's mental commands to the leg muscles. These signals would finally be fed to the nerves that remain connected to the muscles to operate the leg and foot.

The subject would also be able to use feedback, such as watching the legs move and assessing whether they are balanced, to modulate neuronal activity on an ongoing basis. As a result, the movement that the subject is aiming for can be adjusted, promoting learning and increasing accuracy.

Such a system was considered in the United Kingdom in 1994, when a team of scientists implanted electrodes into the spine of Julie Hill, a woman who had been injured in a car crash.[125] They were then able to collect her brain signals and feed them to her muscles through computer-driven technology. After hours of exhausting testing and training, she was able to stand moderately stable, but could not begin walking.

In order to eliminate the problem of balance, the team moved Hill to a sitting down tricycle. By 1997, she was able to train herself and the system to enable her legs to push the pedals in order to power the bike. In many ways, this early attempt of what is sometimes called 'functional electrical stimulation' was a success. But Hill's equipment proved too cumbersome to use and she has now become accustomed to life as a non-walking person.

This experiment demonstrated that inserting electrodes and picking up spinal traffic through filtering the nerve impulses, so that individual nerves could be heard, was a real challenge. Furthermore, even actions as simple as standing require the coordination of many muscles from those controlling the person's toes to those regulating movement in the legs. This means that taking a computer-controlled approach to making a person walk will require tens if not hundreds of connections.

However, in 2016, Swiss scientists indicated that they had been able to treat Rhesus monkeys with spinal cord injuries using a wireless neuroprosthetic interface. This acted as a new bridge between their brains and their spines so that they could regain some control over their legs.[126]

More generally, though, researchers have experienced greater success in functional electrical stimulation when electrodes were strapped to an individual's skin directly over key muscles and a current was passed through the electrodes, making these muscles contract. With correct placement of the electrodes and an appropriate pattern of stimulation, it is suggested that individuals with spinal damage may begin to walk in the future.[127]

Synthetic Cerebellums

In 2011, scientists in Israel indicated that they were able to create a synthetic cerebellum that helps coordinate movements and was able to restore lost brain function in a rat. To do this, the researchers used a chip sitting outside the skull, which was wired into the brain using electrodes. A computer then interpreted input signals and sent a response to a different part of the brainstem (which channels neuronal information from the rest of the body) that initiated motor neurons to implement a certain movement.[128]

In order to check the device, the scientists anaesthetised a rat and disabled its cerebellum before connecting their synthetic version. They then sought to teach the animal a conditioned motor reflex – a blink – by associating a certain noise with a puff of air on the eye, until the animal blinked on hearing the noise by itself. The scientists then tried this without the chip connected and found that the rat was unable to learn the motor reflex. However, once the artificial cerebellum was reconnected, the rat behaved normally and learnt to connect the noise with the need to blink.[129]

This was a proof of concept that computer implants may one day replace areas of the brain damaged by stroke or other conditions. They could then be considered as a kind of cognitive prostheses, with the aim of restoring cognitive function to persons with brain disorders due to injury or disease.[130] Since the hippocampus plays a key role in the recording of memories, they may also assist persons who have suffered brain impairment, such as with Alzheimer's disease, to recover some function.

However, the implant may also be used to enhance healthy brain functions if a person believes that this may be necessary for some reason. [131] In this regard, in 2011, the bioengineer Francisco Sepulveda in the United Kingdom indicated that 'my bet is that specific, well-organised brain parts such as the hippocampus or the visual cortex will have synthetic correlates before the end of the century'.[132]

Non-therapeutic Applications of Feedback Neuronal Interfaces

Nerve Recording Implants

The number of individuals who have made permanent physical connections between their bodies and cybertechnology is relatively small. But one frequently cited example is Kevin Warwick, who in 2002 explored the experience of having a set of electrodes attached to one of the nerves in his arm, which was connected to machines either directly or via the web.[133] The electrode assembly measured 4 mm by 4 mm, but contained a hundred needle electrodes that were just 1.5 mm long. Leading out of the electrode was a long flexible cable connected to externally worn electronics.

Warwick and his team monitored the nerve signals being picked up by the electrodes and sent these through a computer to a robotic hand. Over a number of days, Warwick learned how to move his hand in such a way that the signals, picked up by the computer, could make a robotic hand open and close. In addition, it was able to send back information about how much pressure its 'fingers' were exerting, but Warwick could best drive the system when watching it in action. He also linked the equipment to a wheelchair and was able to start, stop and move in a desired direction.

In another experiment, he travelled to New York, where he linked his implanted device to a web-linked computer and used the signals to drive a robotic hand attached to a computer in the United Kingdom. To an extent, it showed no more than had been achieved in the lab, except that the interface between the two devices was thousands of miles longer.[134] However, this did provide a 'media moment' when members of society could begin to reflect upon the possible outcomes that could be developed through linking out bodies to cyber-aided technology. There is something distinctly intriguing about seeing a piece of machinery move in one continent when the trigger comes from an individual's nervous system on another continent.

The Use of Neuronal Interfaces in Gaming

Most of the gaming neuronal interfaces being developed involve EEG, which records brain activity using electrodes that rest on the scalp or forehead.[135] This activity is then analysed and translated into information that is used to control or bring about effects in computer-operated games.

EEG is often considered for games because it has high temporal resolution and is noninvasive, while being relatively easy and cheap to use. Interestingly, some serious gaming enthusiasts have suggested that in the future, they might be prepared to use other output brain interfaces, such as more invasive and risky implanted electrodes, to enhance their gaming experience.[136]

Currently available commercial brain–computer interface gaming applications use brain signals in the following ways:

- Passive: the output neuronal interface analyses brain signals and interprets this information to bring about a change in the game's environment without the user being in control.[137] The brain signals may also be used to monitor the player's gaming experience so that the game can adjust the level of difficulty.[138]
- Active: players control what happens in the game, through a feedback system, by either (1) imagining movement whereby the neuronal interface analyses part of the brain associated with movement, or (2) changing their overall state by, for example, shifting from feeling frustrated to calm. Some researchers in the Netherlands even created a game in which changes in a player's overall state could transform his or her avatar (an icon or figure representing a particular person in cyberspace) on a screen from a bear to an elf.[139]
- Reactive: the neuronal interface makes use of brain signals from the player associated with event-related reactions by this same player.[140] For example, this can happen when the neuronal interface uses signals from the player when he or she recognises significant information.

However, a number of challenges remain in the development of neuronal interfaces before they can be considered as a standard form of interaction in games. These include the design and characteristics of EEG headsets and how the brain signals are used.[141]

Neuronal Interfaces for Pleasure

In the 1950s, a U.S. physician, Robert Galbraith Heath, was examining how he could address psychological disorders with far less destructive neurosurgery. He did this by drilling very small holes in the skulls of his patients and inserting thin metal probes directly into the brain through which pulses of electricity were administered.

In doing this, Heath discovered that by activating certain parts of the brain, he could stimulate a rush of pleasure that restrained violent behaviours in some of his patients. Moreover, when they were given control of their own pleasure switch, it was even possible for patients to manage the variation in their moods.[142]

Similarly, in 2001, it was reported that another U.S. physician, Stuart Meloy, had patented an implant that initiates an orgasm in individuals at the touch of a button. In this regard, Meloy explained that the Orgasmatron uses implanted electrodes in the spine of an individual to create electrical pulses which initiate waves of pleasure signals whenever the person decides.[143]

Brain Decoding: Reading Minds

Neurological science has not yet reached the stage when the mental state of a person can be read, especially when the person being examined may want to conceal his or her thoughts. But research is now taking place in which computers are beginning to decode a person's thought patterns. Nevertheless, these are very crude experiments with only some elements, such as the images viewed by participants, being recognised by researchers. Such programmes need quite a lot of 'training' to recognise brain activity initiated by a range of images or film clips. In addition, a number of research teams around the world are similarly trying to analyse brain scans in order to determine what people are hearing and feeling, as well as what they remember or even the topic of their dreams.[144]

Such brain decoding began when neuroscientists realised that they could use a lot more of the information they were obtaining from brain scans using fMRI. To do this, scientists divided the three-dimensional brain into voxels (the equivalent of pixels with images) and examined which voxels responded, and in what manner, to a certain stimulus, such as looking at a face.[145] As a result, studies indicate that the responses do not just take place in one specific area of the brain, but in a much more distributive manner. Once the computer has 'learnt' to recognise these brain responses, it can then be used to predict which pictures are associated with which brain responses.

In some of the first studies, researchers were able to identify categories of objects when examining the brain scans of participants looking at objects such as scissors, bottles and shoes.[146] It was then possible, in 2008, to develop a decoder that could identify which of 120 pictures a subject was viewing.[147]

In 2013, other researchers published an attempt at dream decoding. This enabled them to predict, with 60 per cent accuracy, what categories of objects, such as cars, text, men or women, featured in the dreams of the persons taking part in the experiment who were woken up periodically and asked if they could remember what they had dreamt about.[148]

Yet many challenges remain. For example, it is difficult to associate the specific patterns experienced by an individual with the general results obtained from a whole group of persons.[149] But such problems have not discouraged certain companies from trying to use technology, such as neuroimaging, to develop lie detector tests. These would be used to check the truth of a certain statement, the reliability of memories or even any bias in a judge or members of a jury.

Such 'brain reading', if it proved successful, would create a number of significant ethical challenges with respect to privacy and whether a person's thoughts should remain confidential. The media have even speculated that such technology could, one day, bring about some form of telepathy through the continuous use of brain scans.

In this respect, some ethicists do not see any difficulties, in principle, with the development of decoding technologies as long as they are used in the right way. As such, they suggest that brain data should not be considered any differently from other forms of evidence in a court.[150]

Commercially Available Feedback Neuronal Interfaces

A range of commercially available games and other applications that employ feedback neuronal interfaces using EEG are already in existence. These range from simple games with the aim of building monuments from a number of blocks[151] to more complex three-dimensional games, such as making a ball hover in a vertical tube.[152]

In this regard, the least physically intrusive forms of technology are those that can be worn and taken off at will. In other words, they have no permanent connection, require no modification of the user's body and are simply worn like a piece of clothing. Moreover, the non-intrusive nature of these items means that they can easily be tested on people with disabilities.

The EMOTIV Interface

Founded in 2011, EMOTIV is a company that claims its researchers span over 100 countries. Its website indicates that it 'is a bioinformatics company advancing understanding of the human brain using electroencephalography (EEG). Our mission is to empower individuals to understand their own brain and accelerate brain research globally'.[153] Their products are a series of headsets with up to fourteen electrode pads that rest firmly against specific locations on the user's scalp. A connection links the headset to a computer.

There are two ways of using the devices. The first is a passive use in which the player puts on the headset, which then records patterns of activity. In gaming environments, the headset can then respond to the general level of attention, excitement or alertness. If the person is considered to have become bored, it may introduce a new character or challenge. As such, the game can tailor its level of play to each gamer's needs and experience.

Alternatively, users can learn to control their brain activity by, for example, deciding to think of a colour or a game of tennis. With practice, each of these mental activities can produce detectable patterns. Individuals with severe disabilities have found this use very helpful as a means of sending signals to a computer to initiate certain tasks.

Neuronal Interfaces for Portable Appliances

In the world of entertainment, a company called Neurosky has created a product called XWave™, which lets a user read his or her mind via a headset clamped to his or her head and connected to the phone's audio jack. The plastic headband has a sensor that presses against the user's forehead and communicates with a free XWave mobile phone application, which images the user's brain waves graphically on the phone screen. Some of the features being developed on the appliance can then be used to train both the user and the appliance to control certain functions such as choice of music based on the mood of the person.

In addition, if the user focuses his or her mind on a certain task, the graphics on the phone can be changed. For example, the overall level of brain activity can be altered so that, through the software, the person can play games that involve levitating a ball or changing a colour. These games may also become more functional if used by people with physical disabilities who may be able to control screen keyboards and mice.

Immersive Technologies

Ever since electronic games were introduced into public settings, such as bars, around the world, individuals have become used to the idea of interacting with a virtual world. This has seen the virtual nature of that cyberworld become ever more detailed and life-like, with the player being drawn ever more convincingly into the game. In this respect, three key senses are generally involved: sight, sound and touch.

As such, one of the most famous web environments enabling individuals to live virtual lives is Second Life, which is a virtual social network platform allowing its residents to create alternate personalities and avatars, drawing from real and idealised lives.[154]

However, in order to immerse the player even further, it is also possible to step into a CAVE – a Computer Assisted Virtual Environment – which is a cubic room with the walls, floor and possibly the ceiling made up of high-resolution screens. By wearing 3D glasses, the screens become windows into a virtual world surrounding the person on all sides. Using cameras that follow the user's movements, it is then possible for him or her to interact with this new world, such as a new city that a person intends to eventually visit in reality. But it could also be the inner structures of a heart, enabling medical students to acquire unique insights into its workings or enabling a researcher to consider new medical procedures.

A portable version of this sort of product has been developed through the use of head-mounted devices by companies such as Oculus and its Oculus Rift[155] headset. This is a head-worn screen with motion sensors that allow the image to shift as the wearer moves his or her head. The user may also sit at home and obtain the same basic visual experience as being in a big-screen cinema or join with other players to compete in a multiple online game.

Whole body suits extend the experience even further. As well as a 3D head-mounted screen, users can wear motion sensors positioned at all major joints. When they then move through empty warehouse-sized buildings, cameras track their every position and the virtual world image in the headset is changed by the computer using the information from their own sensors and any sensors worn by other players. Already used by some security forces, the technology allows commandos to practise different situations, such as a simulated rescue, which increases their training experiences.

How much of this technology may eventually be bypassed in the future by replacing the information coming from the different senses, such as the visual or auditory senses, with equivalent artificial information which can be sent directly into the brain is an open question. But some neuronal interfaces may far exceed what is presently imaginable.

Sensory Suites

Sensory suites in which a person pulls on a whole or a part of clothing, making it possible to experience certain physical feelings, are also being envisaged. An interface with computers would then exist, which would enable the user to wear the suits and be completely immersed in a computer-generated cyber-environment.

As such, the individual may find it increasingly difficult to know whether he or she is in real or virtual reality. The previously mentioned 'brain in a glass vat' thought experiment, in which the same information from a computer is given to a brain in a vat as is given to a brain in a normal human head, making it impossible for the brain in the vat to know where it is, would then increasingly become relevant.

Neuronal Interfaces and Telepathy

In addition, it has been suggested that a form of telepathy could, one day, be developed through wearable mobile phones that would pick up and send brain signals to users seeking to communicate.[156]

According to researchers at the U.S. company Intel, individuals in the future may no longer need a mouse or a keyboard to control their computers, televisions and mobile phones, since these will be replaced by brain signals.[157] The American Andrew Chien, vice president of research and director of future technologies research at Intel research laboratories, even indicated in 2009: 'If you told people 20 years ago that they would be carrying computers all the time, they would have said, "I don't want that. I don't need that." Now you can't get them to stop [carrying devices]. There are a lot of things that have to be done first but I think [implanting chips into human brains] is well within the scope of possibility.'[158]

But of course, it is always difficult to predict how a market would develop.

Interfaces Used in the Military

Throughout history, military conflicts have been a major driver of technological developments, especially when these are financed by large defence budgets. One example of this is the already mentioned BrainGate™, which received large sums of money from the U.S. Defence Advanced Research Projects Agency (DARPA). This was to conduct research aimed at increasing the speed, sensitivity and accuracy with which a human combatant might analyse information and respond to threats.[159]

In 2010, DARPA also awarded a $2.4 million contract to the company called *Neuromatters* to develop a prototype brain computer interface 'image triage' system as part of its *Cognitive Technology Threat Warning System* research programme.[160] The aim was to determine whether noninvasive brain computer interfaces could enhance the ability of military personnel to analyse intelligence data. This included monitoring brain activity when soldiers looked at images in order to detect any patterns that may be associated with recognising a threat.[161] The results could then be processed in real time to select images that merit further review in order to accelerate decision-making.[162] Similarly, DARPA has funded research on Transcranial Direct Current Stimulation to see if it could be helpful to sharpen soldiers' minds on the battlefield.[163]

However, this U.S. Defence Agency has not stopped there, since it has supported research examining whether neuronal interfaces may be used to control remote weaponry directly from the operators' brain signals.[164] This has resulted in a U.S. patent being filed for 'apparatus for acquiring and transmitting neural signals' for purposes including, but not limited to, weapons or weapon systems, robots or robot systems.[165] In this way, the ability to control a machine through the human brain could even make it possible for a soldier to remotely operate robots or unmanned vehicles in hostile territory.[166]

DARPA has also been interested in finding treatments for injured soldiers, though some could have spinoffs for defence applications and thereby come under the definition of 'dual use' (used for both peaceful and military aims).[167] Indeed, DARPA released a number of calls for grant applications in 2013, including the following:

– Hand Proprioception and Touch Interfaces (HAPTIX) aiming 'to create fully implantable, modular and reconfigurable neural-interface microsystems that communicate wirelessly with external modules, such as a prosthesis interface link, to deliver naturalistic sensations to amputees'.[168]

- Neural Engineering System Design (NESD) aiming 'to develop an implantable neural interface able to provide unprecedented signal resolution and data-transfer bandwidth between the brain and the digital world'.[169]
- Neuro Function, Activity, Structure and Technology (Neuro-FAST) aiming 'to enable unprecedented visualization and decoding of brain activity to better characterize and mitigate threats to the human brain, as well as facilitate development of brain-in-the loop systems to accelerate and improve functional behaviors'.[170]
- Restoring Active Memory (RAM) aiming 'to develop and test a wireless, fully implantable neural-interface medical device for human clinical use. The device would facilitate the formation of new memories and retrieval of existing ones in individuals who have lost these capacities as a result of traumatic brain injury or neurological disease'.[171]
- Reliable Neural-Interface Technology (RE-NET) aiming 'to develop the technologies needed to reliably extract information from the nervous system, and to do so at a scale and rate necessary to control complex machines, such as high-performance prosthetic limbs'.[172]
- Revolutionizing Prosthetics aiming 'to continue increasing functionality of DARPA-developed arm systems to benefit Service members and others who have lost upper limbs'.[173]
- Systems-Based Neurotechnology for Emerging Therapies (SUBNETS) aiming 'to create implanted, closed-loop diagnostic and therapeutic systems for treating neuropsychological illnesses'.[174] SUBNET could, for example, include deep brain stimulators in order to address neurological disorders such as post-traumatic stress, major depression and chronic pain.[175]

In addition, DARPA has been developing a research programme entitled 'Silent Talk', which could facilitate brain-to-brain communication. Interestingly, the possibility of an immediate exchange of thoughts between a number of human beings, using for example a WiFi system, may serve to blur the distinction between an individual's particular sense of self and that of a collective of persons all linked into the same system.[176]

In this regard, the Dublin-based ethicists Fiachra O'Brolchain and Bert Gordijn indicate that: 'Determining the individual consciousness in such a situation may become increasingly difficult.'[177]

Synthetic Biological Brains

Scientists are also considering the possibility of developing synthetic brain organoids which are very small human brains grown entirely in the laboratory. In this regard, ethical challenges would arise if they eventually became conscious in some way. Because of this, Julian Savulescu and the bioethicist Julian Koplin suggest that before such brains are brought into existence in research, it should be demonstrated that the study could not be performed, instead, on non-conscious brain organoids. Moreover, if uncertainty is present, then it is preferable to be over-cautious rather than underestimate their moral status. They explain:

> If these organoids develop sophisticated cognitive capacities beyond mere consciousness – if, for example, they display forms of self-awareness – we might want to attach extra weight to their interests, or even rule out harmful experimentation altogether.[178]

This is important because one relatively new idea in the development of neuronal interfaces takes the form of growing entire human neuronal systems in the laboratory on an array of noninvasive electrodes. This new 'human brain' could then be used, in a similar fashion to a computer, to direct other biological or electronic systems.[179] Such a possibility has already been studied using around 100,000 rodent brain cells on an array. But three-dimensional structures are also being developed that could significantly increase the number of neurons being used.[180]

Human neurons are also being cultured to form synthetic brains, allowing, according to Kevin Warwick, the possibility of 'a robot with a human neuron brain'. However, Warwick does acknowledge that: 'If this brain then consists of billions of neurons, many social and ethical questions will need to be asked.'[181] He suggests that this would especially be true if the robot had the same, or far more, human brain cells as a human being, which may then entitle this robot to human rights.[182]

Ethical Issues Relating to the Technology of Neuronal Interfaces

One of the most important ethical questions arising from neuronal interface appliances relates to their safety and whether the advantages outweigh the considerable risks that may be associated with such technology.[183] Furthermore, the motivation behind using these interfaces should be carefully examined to assess, for example, whether they can be considered as medical interventions and/or enhancements.[184] This is because a new procedure may be considered as an improvement in the context of medicine, but the same technology could also be used for other purposes, such as to enhance normal functions. For instance, the development of human vision beyond the range of what is normally visible would not generally be considered as a medical procedure, since this capacity has never previously existed in human beings. Questions can then be asked whether such an enhancement could be considered as beneficial for the individual, or for the whole of society, if it were possible, for instance, to make night driving a lot safer.

It is also important to consider the personal autonomy of an individual in choosing what risks to take in the context of a societal decision about which enhancement technologies to allow. This implies that if it can be shown that the risks arising from the enhancement are minimal, the burden of proof should generally lie on those who would argue that the enhancement should not be used. In the light of this, an important question relating to enhancement technologies is whether it would be possible to prepare guidelines and regulations concerning the kind of technology for which societal approval may be necessary, thereby restricting personal autonomy.[185]

Risks Related to Noninvasive Neuronal Interfaces

It is worth noting that with noninvasive output or input neuronal interface systems, such as EEG, some elements of risk remain. Amongst a number of challenges, this is because of the inherent plasticity of the brain with respect to function or structure as a result of interfaces requiring a highly repetitive use of certain applications. A lot of time may be required for a user to learn how to generate certain brain electrical signals in order to control a device. The performance of a user may also be dependent on how tired he or she feels, as well as any distractions or other external influences.[186] However, it should be recognised that in any learning process, such an effort is usually required.[187]

Risks Relating to Invasive Neuronal Interfaces

Ever since it has become possible to implant devices into the nervous systems of individuals, it has been necessary to consider the risks such applications create. Moreover, from the earliest analyses of these risks, it is clear that a consensus about what the unintended risks (or benefits) might be is difficult to find.[188]

Implanting a device, such as an electrode, into a certain brain area is very likely to have lasting effects. This is because once it becomes integrated into the tissue, its subsequent removal may give rise to serious damage. It is therefore important to consider whether better technologies may be available in the future and whether all the information about the optimum location for implanting the device has been provided to the prospective patient.[189]

Any activity in the brain will also cause other brain cells to migrate towards, and cluster around, the device. Indeed, some of these cells will recognise the implant as being foreign to the body and will then work hard to destroy or evict it. Furthermore, if an electrode is implanted, this clustering will most probably eventually interfere with its ability to pick up or give signals.[190] But much progress has been made in recent decades into developing materials that resist rejection. For instance, nanoscale coatings on surgical implants may give enhanced biocompatibility. However, it is still necessary to assess the risk of abrasion in long-term use and the possible release of nano-particles into the brain.

Connecting the device with the outside world also creates challenges. Implanting any item into brain tissue will cause local neuronal and vascular damage and will introduce an increased risk of infection.[191] The first devices all relied on wires reaching from the electrodes through the skin, but the exit site for these wires could give rise to possible infections, with the wires forming a surface along which bacteria can travel. Moreover, the wires themselves can easily act as aerials, picking up radio signals or electrical interference from the surrounding environment. If this occurs, the device may malfunction or the information it is transmitting may be lost in the midst of the 'noise'.[192] However, future wireless appliances may be able to partially address some of these challenges.

In normal situations, a person often has a number of different ways to help him or her communicate, such as talking, waving a hand or in more extreme situations blinking. If a person believes that others have misunderstood what he or she wanted, he or she can reinforce or correct the message by doing something. But in some situations where neuronal interfaces are used, such as when a person is locked-in, communication through the device may be the only means of conveying a message. If that information is disrupted through interference, then the person has no secondary means of correcting the situation.[193] Thus, a system linking a brain to a wheelchair would need to seriously consider a secondary safety system in order to prevent dangerous or unintended movements.

Biological risks relating to neuronal interfaces should also address the long-term consequences that may not be envisaged at the beginning. For example, it may eventually be necessary to remove a device because it became defective, less effective or worn out. This means that in the case of implants, reversibility and controllability are significant factors. If something goes wrong, it is important to consider whether the device could be taken out of a person, replaced with a new or more improved system, or even just deactivated.

On this account, when the medical conditions being considered are very serious, it may be acceptable for greater risks to be taken in implanting devices. The advantages of invasive and partially invasive output systems, with respect to the accuracy of recording brain signals, should then be examined against the considerable disadvantages that the person may already be experiencing.

However, in the context of enhancement, very different risk-benefit ratios would exist. Indeed, if the system was only a means of enhancing a normal situation, the risks would need to be minimal at best.[194] This means that invasive neuronal interfaces used for enhancement purposes may remain in the distant future.

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