FEATURE

The age of the superhuman

Christian Jarrett gets to grips with cyborg technology

Mention cyborgs and thoughts usually turn to the deadly man–machine hybrids that stalk the world in sci-fi films. But cyborgs are already here. It's not just pacemakers and replacement hips. Hundreds of thousands of people have bionic sensory implants interfacing with their brains; mass-market mind-controlled prosthetics are around the corner; and for most of us, our mobile phones have become extensions of our minds. All the while, companies like Google are busy working on devices that promise ever greater person–machine integration.

Replacing broken parts

Definitions of cyborgs vary, but a popular criterion is that there is an embedding or melding of technology with the biological human form, especially the brain. The most ubiquitous way this is already happening is in the use of bionic implants to replace lost sensory functions.

Take the cochlear implant. Many deaf people have an intact auditory nerve but they have lost the function of the hair cells found in the snail-like cochlear located in their inner ear. The cochlear implant acts as a replacement for these cells and translates sounds into electrical impulses that stimulate the still-functioning auditory nerve.

After several experimental prototypes through the 1960s and 70s, effective cochlear implants have been commercially available since the 1980s. For people born deaf, the timing of the implantation makes all the difference. Because of the way the auditory cortex develops, the earlier a congenitally deaf child can receive a cochlear implant, the better, at least in terms of their speech development. In a review published last year, Andrej Kral and Anu Sharma wrote that implantation at primary-school age or later means normal speech production and understanding will not be achieved.

But this is a controversial issue – deaf children with an implant tend not to learn sign language and so don't become part of the mainstream deaf community. Kral who's based at the Institute of Audioneurotechnology and Department of Experimental Otology, Hannover School of Medicine, makes a distinction between the vast majority of deaf children who are born to hearing parents, and the minority of deaf children born to deaf parents. The latter he believes should be raised bilingually with speech and sign. 'The best therapy is the very early implantation that gives the child the opportunity for taking the best of both worlds – the signed and spoken,' he says.

Although at a far more experimental stage of development, implants are also available to compensate for blindness caused by degeneration of photoreceptors in the retina. The implant converts light into a signal that stimulates the retinal ganglion or bipolar cells, which would normally receive input from the lost photoreceptors. In turn, these intermediate cells pass on the signal to the optic nerve and into the brain.

In 2011 the Argus II, made by the California company Second Sight, became the first retinal implant to receive a licence for use in Europe (FDA approval in the States followed earlier this year). Users vary in what they can see, but most report patterns of light, movement and colours, and in some cases even the ability to read short sentences. An early patient, Ron 'the man with a bionic eye', told the BBC in a 2009 documentary: 'After you've seen nothing for 30 years but darkness,

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suddenly to be able to see light again is truly wonderful.’

These results sound promising, but Gislin Dagnelie at the Lions Vision Research and Rehabilitation Center, Johns Hopkins University School of Medicine, warns us not to get carried away. ‘All types of implants that connect with the remaining retinal cells in patients whose rods and cones have been destroyed by disease will have to become much more sophisticated before the information they convey will allow implantees to perform routine everyday tasks like reading and fine hand–eye coordination,’ he says.

Aside from the inevitable risks and strain of the surgery required to insert an implant, the initial programming of the device and subsequent visual training also remain lengthy, arduous procedures. From a psychological perspective, there’s a need to manage and monitor patient expectations and coping. Promisingly, the first ever study to look at the well-being of retinal implant patients, led by Tobias Peters, found that levels of psychological distress actually improved over the course of a retinal implant trial.

Connecting with external technology

Another form of cyborg technology that may soon be licensed for clinical use is a brain implant that allows patients to interface mentally with an external prosthetic limb or other device. In 2012 researchers reached a new milestone by demonstrating that this technology could enable paralysed patients to use thought-power to reach and grasp objects with a robotic arm. The research, led by John Donoghue at the Institute for Brain Science, Brown University, involved a microelectrode array – ‘BrainGate’ – being implanted onto the surface of the patients’ motor cortex.

This was an advance on earlier attempts at brain–machine interfacing, which relied on recording the surface electrical activity of the brain and required weeks or months of training. Patients were also unable to converse or engage in other activities while concentrating on controlling their brainwaves. The BrainGate device works differently: patients imagine moving their lost limb and hair-thin electrodes record the resulting neural activity, translating it into commands for the robot arm.

Despite these advances, significant hurdles remain. Implantation of the electrode array requires significant surgery, and to function it has to be connected to

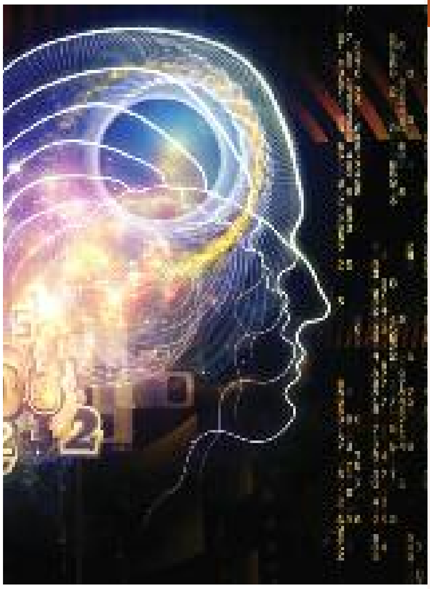
Advocacy and ethics

At what point should society treat an item of technology as part of someone’s body? Neil Harbisson, a colour-blind man, confronted this issue when he was prohibited from appearing in his passport photo wearing an eyeborg – a sensory substitution device that converts colour into sounds that vibrate the user’s skull. After campaigning and winning permission to wear the technology, Harbisson claims to be the world’s first official cyborg recognised by a government.

In 2010 he started the Cyborg Foundation based in Barcelona, its mission to ‘promote the use of cybernetics as part of the human body and to defend cyborg rights’. Other prominent cyborg advocates include Guiseppe Vatinno, the world’s first transhumanist politician (in the Italian parliament), and Kevin Warwick, a cybernetics professor at the University of Reading who has previously wired his own nervous system to the internet (see ‘Kevin Warwick: real-life cyborg’, p.723).

Other commentators, such as the ethicists Jens Clausen and Ellen McGee, warn there is an urgent need for a discussion about the ethical implications of cyborg technology. Until recently the emphasis on technological implants has mostly been on restoring lost function, but in the near future the extension and augmentation of normal function is likely to become ubiquitous. This raises the potential for social division between those who can afford and wish to become cyborgs and those who can’t or don’t. Another risk is that a burden will be placed on people with disabilities to use technology to compensate for their impairments, rather than society adapting to their needs.

Deep brain implants that alter behaviour and interfere with reward processing raise further specific concerns about a loss or alteration to personhood. Brain–machine interfaces pose other issues around volition and responsibility. Who is culpable if a gun shot is fired by a mind-controlled prosthesis that malfunctions, and how easy will it be to prove that malfunction? McGee and others have gone further – what if implanted technology is exploited by governments or corporations to monitor and control citizens?



Deep brain implants that alter behaviour raise further specific concerns

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a computer via bulky cables (Donoghue's group say they are working on a wireless version that will soon overcome this problem). Another limitation is the lack of proprioceptive and tactile feedback from the robot limb – sensations which we take for granted when controlling our natural limbs. However, progress is being made on this front too.

At the Association for the Advancement of Science conference held in Boston this year, Miguel Nicolelis, a neurobiologist at Duke University in North Carolina, presented new research showing that rats were able to detect infra-red light after an electrode (receiving infra-red information) was inserted into their somatosensory cortex. This development paves the way for prosthetics that release pulses of infra-red light, detect the rebound, and send the information to the brain where it could be interpreted as a touch-like sense for the artificial limb. It also demonstrates a proof of principle for technology to support sensory extension, potentially allowing humans to detect information, such as X-ray light, that is currently beyond their reach.

Stimulating the brain

As well as recording brain activity, neural implants can also be used to deliberately alter brain function. Implants that stimulate the brain are being investigated as a therapeutic treatment for mental illnesses like anorexia, major depression and OCD. However, it is for the neurodegenerative condition Parkinson's that the technology has already been adopted in clinical practice for patients who don't respond to drug treatments. In this case, the electrical stimulation is used to rebalance function in the motor systems of the brain.

So far, we've heard about embedded technology being used to replace or ameliorate lost sensory or motor functions. However, a run of recent studies has also shown the potential for external brain stimulation techniques to augment healthy mental functioning, thus raising the prospect of the proverbial 'thinking cap' becoming a must-have accessory.

Generating particular excitement is transcranial direct current stimulation (tDCS), which involves placing electrodes directly on the scalp to apply weak electrical currents to the brain, affecting its function. A team led by Janine Reis at NIH showed in a 2009 paper that anodal (positively charged) stimulation over the motor cortex led to enhanced learning of a complex motor task. More recently, in 2010, Cohen Kadosh and his colleagues reported that tDCS over the parietal lobes enhanced numerical skills. And just last year a team at UCL targeted the temporal-parietal junction and found that stimulation here improved participants' performance on a social task that required perspective taking.

Part of the reason for the raised expectations around tDCS is that the equipment is extremely portable (unlike the machinery required for transcranial magnetic stimulation – another technique used for cognitive enhancement). Indeed, home tDCS kits can already be purchased on the internet for less than $200 and there are YouTube videos explaining how to build your own device.

The accessibility of the technology and the hype around its potential applications has prompted several neuroscientists to warn about the urgent ethical issues this raises (see 'Advocacy and ethics', p.721). In an essay published last year Cohen Kadosh and his colleagues warned that little is known about the best way to use the technology, and that it would be especially easy for amateurs or untrained clinicians to stimulate the wrong brain areas. The authors raise particular concerns in relation to young children – the effects of stimulation are particularly unpredictable when it comes to the developing brain and there are issues around children's ability to give their informed consent.

'tDCS alone is of little use,' says Cohen Kadosh. 'The advantage of it is when it is combined with a cognitive training, rather than just applied alone to the brain. You need to know which brain region to target, and this is defined based on different factors including the type of training, the age of your subject, and his/her cognitive abilities. In addition, people might be tempted to stimulate too much, and by this cause damage, rather than any improvement.'

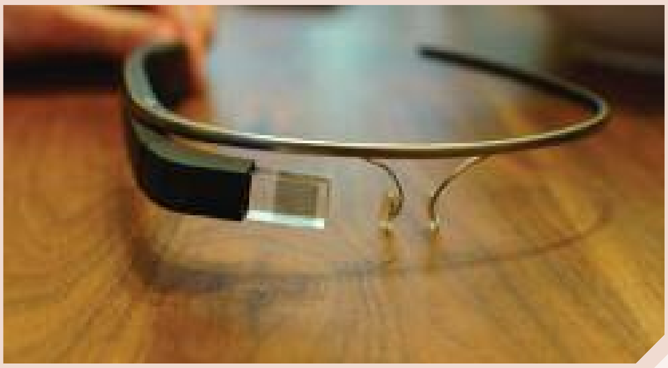
Another worrying factor is the possibility that enhancement in one domain could lead to a detriment of function in another. This possibility was made plain in a study Cohen Kadosh published with Teresa Iuculano earlier this year, in which 19 participants spent time learning new numerical symbols. tDCS over the parietal lobes accelerated the learning, but it impaired the process whereby this knowledge became implicit. Stimulation over dorsolateral prefrontal cortex had the opposite effect. 'I am not against enhancement,' says Cohen Kadosh, 'but we need to know the best way to optimise it, and at the moment we are still experimenting.'

Extending the mind

The cyborg revolution is not just about replacement parts, brain recording and brain stimulation. There's also an increasing sense that we're outsourcing our minds to digital technology. 'When I write with a browser open in the background, it feels like the browser is an extension of myself,' said psychologist Stephen Kosslyn in answer to an annual Edge.org question about the effects of the internet. For Geoffrey Miller at the University of New Mexico, sites like BBC News are extending his perception, 'becoming my sixth sense for world events' (find all the answers at tinyurl.com/aht2zat).

These feelings were lent empirical support in a 2011 study that tested people's memory for trivia facts they'd typed into a computer. Those told that the computer would save their entries were far less likely to recall the correct facts than those told that the entries would be deleted. A follow-up study found that people were better at remembering which folder they'd typed entries into, rather than the entries themselves. 'One could argue that this is an adaptive use of memory,' Sparrow and her colleagues concluded, 'to include the computer and online searches as an external memory system that can be accessed at will.'

Any merging of our minds with Google is only likely to increase in the near future as the company joins others in the industry in seeking new ways to incorporate the internet into our daily



Google glass – a form of wearable computing that feeds the wearer information from the internet about what's in front of them

Kevin Warwick: real-life cyborg

In March 2002 a 100-electrode 'BrainGate' implant was fired into the median nerves of my left arm in a two-hour neurosurgical operation in Oxford. This was the first time the implant had been used in any human and it successfully remained in my nervous system for just over three months.

Once the implant was in place the experiment involved several features:

1. The control of a robot hand directly from neural signals, along with proprioceptive tactile feedback from sensors in the hand's fingers.
2. This was repeated with myself in New York and the hand in England, so I could feel the force applied by the hand. My nervous system was extended over the internet.
3. Use of extra-sensory, ultrasonic input to give me a good sense of distance to objects.
4. My wife also had electrodes implanted and we communicated telegraphically, nervous system to nervous system.

I did not need the implant for medical reasons, this was carried out for scientific and medical experimental purposes. Partly it was to assess the potential use of such an implant for paralysed patients (for which it subsequently is being successfully used) and partly to investigate the potential of the human brain to take on, understand and make use of opportunities such as new senses. So it involved both therapy and enhancement aspects.

Carrying out such an experiment in 2002 raised many technical challenges in getting the human nervous system and a computer network to communicate with each other. It proved to be an enormous learning experience as well as an exciting, pioneering experiment into cyborg technology.

Whilst it is clear that such technology can enable those who are paralysed, it is worth remembering that all humans are severely limited in what we can do and how our brains perform. Such technology opens up the distinct possibility of human enhancement, co-evolving with our technological inventions, just as science fiction has predicted.

activities. In January this year, Google co-founder Sergey Brin was spotted on the New York subway sporting a pair of hi-tech glasses that feature a miniature screen that displays data to the wearer. Known as Google Glass, the soon-to-be-available device is a form of wearable computing that feeds the wearer information from the internet about what's in front of them, as well as, potentially, broadcasting the user's perspective to the world.

The future

The cyborg developments discussed so far are either already here or soon will be. Looking further into the future we find the promise of substitute brain parts, implanted gadgets, and even virtual immortality. In 2011 Matti Mintz of Tel Aviv University in Israel replaced part of a rat's cerebellum with a chip that imitated the lost function. Unlike a brain implant that sends signals from the brain to an external device, this research demonstrated it's possible to record a signal from one part of the brain, analyse it and then send an onward message to a different brain system. It's an exciting proof of principle that could lead to digital solutions for tomorrow's brain-damaged patients.

Meanwhile software researchers at Autodesk in Toronto reported last year on their grisly research with human cadavers, which demonstrated conventional consumer gadgets still function and interface as usual when they're embedded in human flesh. According to a report in *New Scientist*, there are still issues around infection prevention and the replacement of broken devices, but the day is surely coming closer that we will have our mobile devices fully merged with our bodies. In a related development, another group based at the University of California at San Diego is working on tattoo-like circuits that can detect surface brain waves, or localised muscle activity from the body. This increases the feasibility that we might soon control domestic products or vehicles merely with our thoughts.

What if we end up with so many embedded computer parts that we're more machine than person? Bruce Hood at the University of Bristol and author of *The Self Delusion* believes this could pose an interesting challenge to our sense of self and identity. 'Like the proverbial Ship of Theseus, most of us believe that we are more than the sum of our parts,' he says. 'We cut our hair or nails but we do not feel we are diminished. We can even lose an organ or a limb and remain the same person. But where does one draw the line? What about losing one neuron or two? Or indeed replacing them with someone else's or an artificial mechanism? Inevitably as our technologies develop to repair and replace our bodies, we must eventually accept that we are not the individuals that we think we are.'

The 2045 initiative launched by Russian entrepreneur Dmitry Itskov in 2011 takes this idea to the extreme. The movement accepts the prediction by influential US futurologist Ray Kurzweil that within a few decades it will be possible to replace all human parts with technological substitutes. The project's ultimate goal is for us to be able to upload our minds into a non-biological body, thus making us immortal. There are, not surprisingly, serious grounds for scepticism – Nicolelis, for one, is on record saying it will never happen because the brain is 'not computable'. Nonetheless, you may want to put 2045 in your diary. This, according to 2045.com, is 'the time when substance-independent minds will receive new bodies with capacities far exceeding those of ordinary humans. A new era for humanity will arrive!'

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