Innovation Network | Neurotechnology

Towards a UK Neurotechnology Strategy

A UK ecosystem for Neurotechnology: Development, commercial exploitation and societal adoption

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Positive Change.

We will create a shared vision for the UK to be a world leader in neurotechnology.

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[1] https://www.internationalbraininitiative.org/

Executive Summary

Recent funding initiatives have changed the global neurotechnology landscape, with the US, China, Japan, the EU, Canada and Australia all investing at scale in 10 year+ programmes. In particular, the US has seen an investment of $1.7 billion since 2014 in their national programme[1]. The resultant rapid maturation of the academic research has led to sophisticated clinical devices capable of treating neurodegenerative conditions in patients and to a burgeoning commercial sector. The UK, with its outstanding neuroscience, medical and engineering expertise, has an exciting opportunity to make a valuable contribution to the leadership of this international effort.

Vision: In response to this opportunity our vision is to bring together the existing strengths and form a cohesive UK eco-system to accelerate commercial and economic opportunities from neurotechnology science and engineering research. We will create a shared vision for the UK to become a leading place for neurotechnology industry, workplace skills, inward investment and societal impact. We will work with translational centres to accelerate technology exploitation routes and enhance options for anchoring research and development in UK companies.

We propose a UK-wide initiative focused on advancing the state-of-the-art in neuromodulation for both the treatment of neural disorders and non-medical neurotechnologies. Engineers will work in tandem with neuroscientists to understand the neural basis of the clinical condition and ascertain the optimal technological approach to treatment and commercial applications. For medical applications, our approach will engage with clinicians at the outset, to identify unmet clinical needs. The commercial sector, alongside regulatory bodies and the NHS, will be integrated at the earliest stage to ensure translation and societal benefit is at the fore.

[1] https://www.internationalbraininitiative.org/

A UK Eco-System for Neurotechnology: Development, Commercial Exploitation and Societal Adoption

Advances in smart and novel technologies are opening up many new possibilities for treatment of degenerative neural conditions. As a result, these technologies are becoming recognised as an exciting prospect for development and substantial investment from funders and venture capitalists.

The need for these technologies is critical - mental illness is the leading cause of illness in the UK, with costs estimated at 4.5% of UK GDP (£70 billion - OECD report, Oct 2014). This is compounded by the fact that there has "not been a fundamentally new class of drugs for psychiatric disorders since the 1970s"[2] – due mainly to our limited understanding of brain circuits and how pharmaceutical approaches affect them. In parallel, the UK Government estimates that more than 10 million people in the UK will see their 100th birthday[3]. Increasing life expectancy is set to be one of the greatest challenges of this century and will have significant impact on the NHS and social care expenditure. In 2010, spending on health conditions associated with age already accounted for 70% of the total health and care spending in England[4].

Significant opportunity exists in the UK for a more joined up approach and co-investment between policy, research, technology, clinicians and the public.

Globally, neurotechnology products – defined as "the application of electronics and engineering to the human nervous system" – will be $15 billion in 2024[5]. Crunchbase identifies 250 neuroscience start-ups and companies with an average valuation of $4 million.

Examples include:

- $100 million investment into Kernel, 'a neuroscience company focused on developing technologies to understand and treat neurological diseases and radically improving our cognition';
- $158 million invested in Neuralink, founded by entrepreneur Elon Musk, to develop 'ultra-high bandwidth brain-machine interfaces to connect humans and computers';
- Galvani Bioelectronics, formed by GlaxoSmithKline and Verily Life Sciences – part of Google's parent company, Alphabet – is planning to invest £540 million over seven years to develop 'tiny implantable devices to change precise electrical signals in nerves to treat a range of debilitating chronic diseases';

BRAIN INITIATIVE

The Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative is the US government program, funded from 2014 to 2026. The strategy is to develop novel neurotechnology that will revolutionise our understanding of the human brain. The vision is to produce a dynamic picture of the brain that, for the first time, shows how individual cells and complex neural circuits interact in both time and space.

To date this initiative has funded over 735 awards across 100s of investigators, with over $1B invested and more than 600 publications resulting. A further $3B investment, through to 2026, is planned.

[2] https://braininitiative.nih.gov/strategic-planning/brain-2025-report
[3] https://www.gov.uk/government/news/government-announces-300-million-for-landmark-ageing-society-grand-challenge
[4] https://www.parliament.uk/business/publications/research/key-issues-parliament-2015/social-change/ageing-population/
[5] https://www.neurotechreports.com/pages/execsum.html

The UK

Academically the UK has strong neuroscience and engineering research (e.g. UCL's neuroscience research is the most cited in Europe and second most cited in the world). However, these UK communities lack a mechanism, such as the US BRAIN initiative, to provide the cohesion required to fully exploit the combined potential. Key strengths of the UK mean it is well positioned to become a world leader in next-generation neural interfaces technologies[6]. These include:

- Academic excellence in relevant disciplines, from neuroscience to electrical engineering;
- Supportive regulation – with an internationally renowned regulatory system that is taking a new approach to accelerate responsible innovation in emerging technology;
- The NHS – providing a unified national platform for research, innovation and commercialisation;
- Competitive advantage provided by a dynamic life sciences sector and thriving creative industries.

In recent years, the UK Government has recognised the Ageing Society Grand Challenge, investing £300 million to stimulate industry and academic collaboration. As part of this, £40 million was invested in a new hub for UK Dementia Research; £98m for a 'healthy ageing programme'; £210 million 'for data to early diagnosis and precision medicine programme' to improve diagnosis of disease and develop new medical treatments and technologies; with other funding for the development of new products and services to help people live longer.

[6] https://royalsociety.org/-/media/policy/projects/ihuman/report-neural-interfaces.pdf

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Despite strengths and investments, the UK needs to achieve the following to become world leading[6]:

1. Establish a collaborative 'ecosystem' that draws together a range of specialists including neuroengineers, electrical engineers, neurologists, psychologists and policy/regulation experts;

2. Enable a collaborative support community to take on regulatory and project management challenges, associated with translating technologies from prototypes to clinical trials and meeting regulatory and legislative requirements;

3. Create joint initiatives between different types of funders, such as research councils, Innovate UK and charities;

4. Build strong academic-medical links. More efforts are needed to encourage clinicians in training to engage in research;

5. Identify the skills gap and opportunity for training the next generation of multi-disciplinary teams;

6. A continued engagement with the general public about neurotechnology (following on from the work done by the Royal Society);

7. Create a comprehensive ethical framework for neurotechnology;

8. Long term funding mechanism for industry to support high risk projects.

[6] https://royalsociety.org/-/media/policy/projects/ihuman/report-neural-interfaces.pdf

Table 1 highlights some of the major challenge areas for the UK neurotechnology sector and identifies some examples of challenges such as, creating manufacturing facilities so UK companies have the ability to build medical devices for clinical trial here in the UK rather than overseas. This will be further developed during a Deep-Dive workshop in October 2020.

Table 1. Challenge areas for UK Neurotechnology

Challenge Area	Goal	Example Challenges
Neurotechnology for Mental Health	Create and scale treatments for mental health	– In-home treatment for anxiety – Wide adoption in the NHS of Transcranial Magnetic Stimulation as a treatment for depression – Improved sleep
Neurotechnology for Healthy Ageing	Create novel treatments for chronic conditions	– In-home stroke rehabilitation – Early diagnosis of dementia – Bioelectronic medicine to treat diabetes, hypertension and rheumatoid arthritis – Non-invasive treatments for neuropathic pain
Neurotechnology for Physical Disabilities	Create novel neuroprosthetics	– Exoskeletons controlled by brain-computer interfaces – 'Near-Perfect eyesight' retinal prosthetics
Non-Medical Neurotechnologies	Create new ways to interface with machines	– Truly immersive gaming with brain-computer interfaces integrated into VR headsets – Augmented decision making using AI
Neurotechnology Commercialisation	Accelerate the pathway from unmet need to product	– Gather clinical unmet needs – Clear pathway for new medical devices from bench to clinic – Embed MHRA in the ecosystem – Create an ethical framework – Public engagement
Neurotechnology Manufacturing	Grow a supply chain to manufacture neurotechnology in the UK	– Scale up from 15-500 devices for clinical trials – Large scale manufacturing facilities – Integrated supply chain

Our Proposed Approach

Draw together the key UK communities – academic, industrial and medical via a "Neurotechnology Deep-Dive workshop" – in October 2020.

Engage wider with identified stakeholder communities – including industry - seeking feedback and input/validation to a white paper.

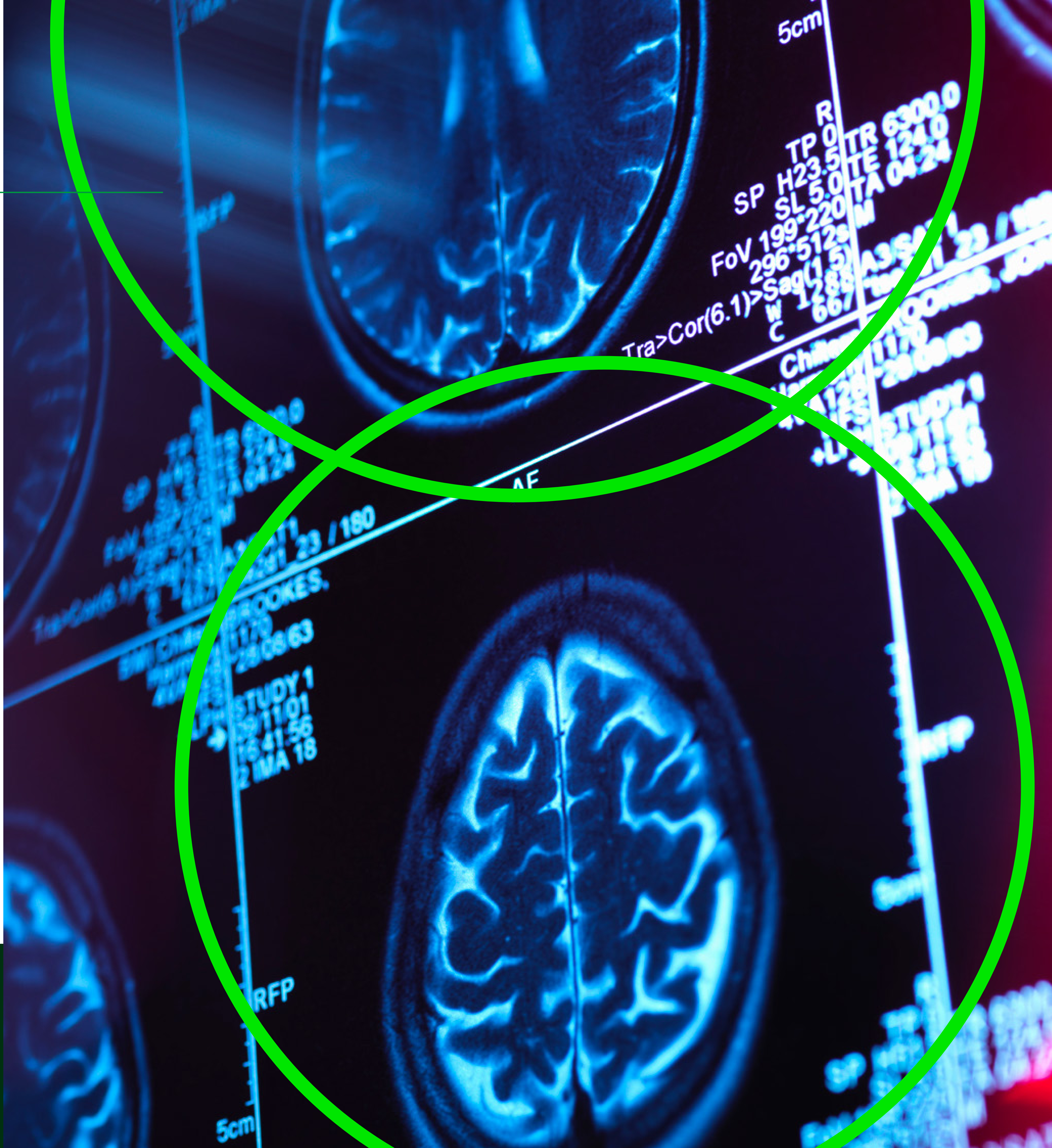
Identify the requirements around graduate training to ensure the emerging commercial sector has access to a highly trained workforce with the required interdisciplinary skills.

Hold an event, hosted by the Royal Academy of Engineering, bringing funders and decision makers together with the UK neurotechnology community to report on the outcomes of the Deep-Dive workshop and deliver the UK Neurotechnology Strategy.

Submit a paper to UK Government recommending next steps and opportunities.

Form an inclusive grouping to drive forward a UK roadmap for neurotechnology.

We expect these activities will result in a UK roadmap for neurotechnology that will provide strategic guidance to academic, industry and government stakeholders and align the ecosystem for global leadership.



Case Study: Retinal Prosthetics

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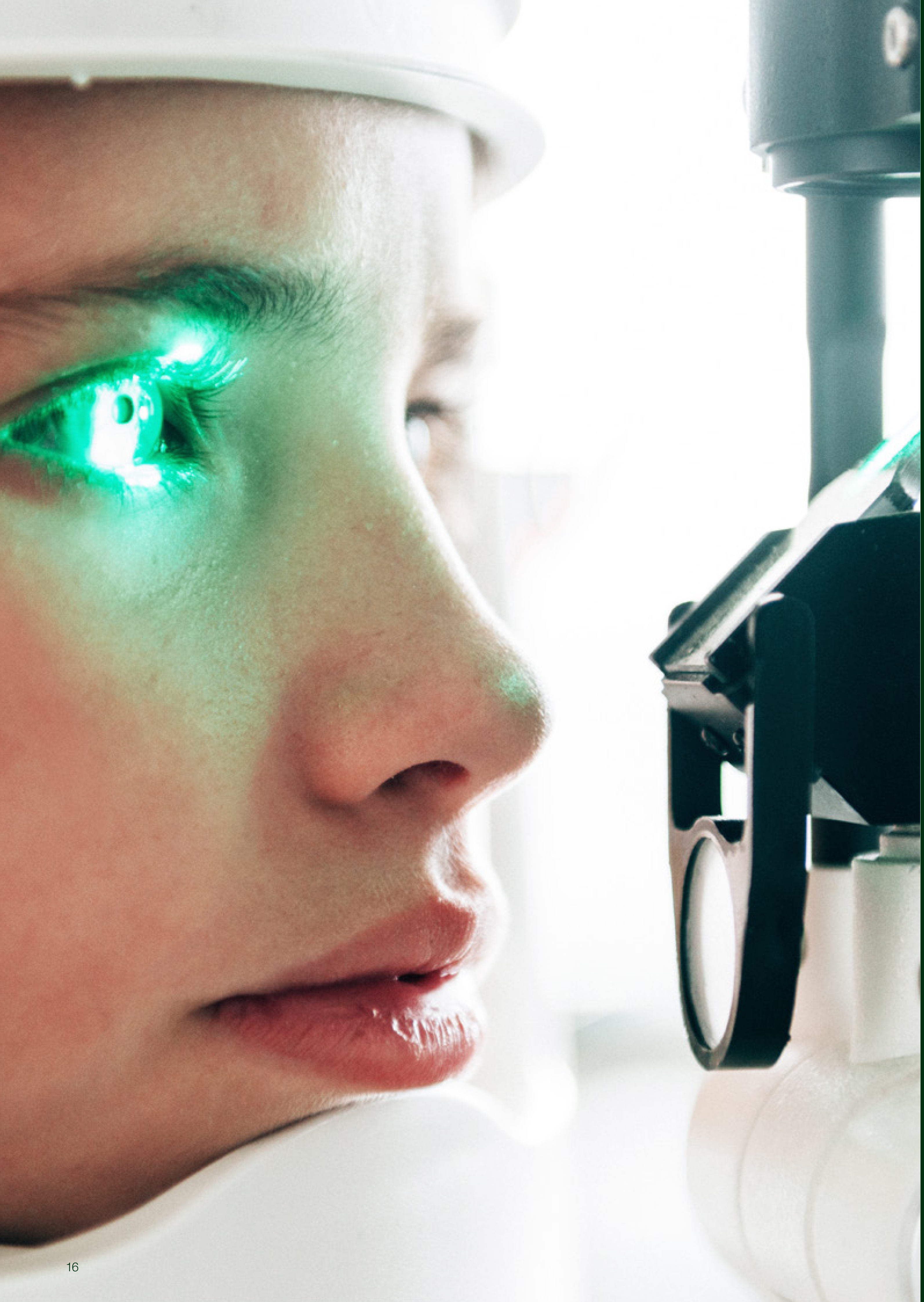


Retinal Prosthetics

The field of retinal prosthetics is a good example of how advances in neural interfacing are beginning to translate a promising technology into an appealing clinical approach. There have been worldwide efforts over many decades attempting to restore vision to patients suffering from degenerative retinal conditions. Typically employing spatially patterned electrical stimulation of the retina that is controlled by an external video camera. Early successes led to clinically approved products from companies such as Second Sight and Retinal Implant AG.

These efforts were pivotal in driving the research field forward yet failed to have significant clinical impact. There were many reasons for this, but one of the most important was that the visual acuity restored to patients, was poor. So, while they demonstrated important proof of concept, there was not the clinical impact for a substantial patient cohort that could sustain a significant commercial opportunity; both companies have now ceased operation.

In particular, Age-related Macular Degeneration (AMD) affects approximately 200 million people worldwide, by destroying the high-resolution, central vision in patients. Restoring low visual acuity in these patients has very little clinical benefit as they typically have their peripheral vision intact. However, recent advances in neural interfacing are now demonstrating a restored visual acuity in patients that is becoming clinically appealing. Engineers and scientist, working in tandem with neuroscientists identified the neural pathways to activate and optimised the stimulation techniques accordingly. Clinical trials are now demonstrating a restored visual acuity in patients far beyond previous work, with a clear pathway identified to restore useful vision to AMD patients.

This multi-disciplinary approach of understanding the underlying neural circuitry, optimising the neurotechnology and engaging closely with clinical partners, is opening up a significant commercial opportunity with the prospect of substantial impact for an aging society.

Uses of Neurotechnology

Neurotechnology ranges from the measurement of the whole brain through technologies such as electroencephalography (EEG) to the stimulation of a single nerve using bioelectronic medicines. Whilst these technologies are currently used independently, it is likely that neurotechnologies of the future will use a combination of these spatial resolutions to enable both broad range and fine grain measurement and stimulation.

Neurotechnology has been used to help people with spinal cord injury to walk again with the use of brain implants that communicate wirelessly to implants near their limbs, bypassing the damaged spinal cord[7]. Intracortical microstimulation of primary somatosensory cortex could help people control and receive sensory feedback from prosthetic limbs[8].

Deep brain stimulation continues to be an exciting research area, with strong clinical implications. It can now almost completely stop the tremors caused by Parkinson's[9] and has been shown to significantly reduce the chance of epileptic seizures[10]. Recent research has even demonstrated that it can improve memory for people suffering from early stage Alzheimer's[11].

Advances in technology have the potential to provide the tools for quicker diagnoses, more effective treatments and increased accessibility for people suffering from mood and psychotic disorders. Transcranial magnetic stimulation (TMS), was pioneered in the UK and is now being driven forward by Wales-based Magstim. It is a non-invasive procedure which is approved to treat severe depression. A recent study for the NHS has demonstrated that microcurrent electrical stimulation therapy is an effective treatment for people suffering from Generalized Anxiety Disorder and is a cost-effective treatment, with a saving of £540 per patient, compared to other available treatments[12].

Bioelectronic Medicine

Bioelectronic medicine is an emerging field where electrical devices read and modulate signal patterns passing through the peripheral nervous system. Chronic diseases and disorders such as rheumatoid arthritis, inflammatory bowel disease, diabetes, hypertension and asthma could potentially be treated using these devices. Not only will bioelectronic medicines be able to treat diseases with more precision than conventional pharmaceutical medicines, but they should also have fewer side effects and could be far more cost effective. UK-based Galvani Bioelectronics is a key player in the area.

Setpoint Medical in the US have shown that a bioelectronic device placed on the vagus nerve in the neck can inhibit cytokine production, greatly reducing inflammation for people suffering from rheumatoid arthritis. Over 400,000 people in the UK have rheumatoid arthritis. A third of people with rheumatoid arthritis will have stopped working within 2 years of onset and half will be unable to work within 10 years[13]. The National Audit Office estimates that rheumatoid arthritis costs the NHS £560 million[14] with total costs to the UK economy of £3.8-4.8 billion per year[15]. Vagus nerve stimulation may be able to achieve remission in 20-30% of patients including patients who have not responded at all to modern pharmaceuticals[16]. Cost savings of even just 10% with the use of vagus nerve stimulation would save the NHS £56 million and £380-480 million for the wider economy each year.

Brain-Computer Interfaces

Brain-computer interfaces are devices that establish a direct communication and control channel between humans and machines. We currently type at our keyboard and move the mouse with our hands, or perhaps give an instruction to a voice assistant. These input methods are inherently slow compared to the speed of our brains and the computers we are working with. BCIs give us the ability to bypass our hands or voice and communicate with and control computers directly with our mind.

The brain's electrophysiological signals can be recorded over the scalp, under the scalp or within the brain. These signals, intentionally modulated by the user, are processed in real time, and translated into output commands. The user then obtains feedback about the success or failure of their efforts to communicate or control.

BCIs have already been used to help paralysed people walk using robotic exoskeletons and allowed us to communicate with people that are "locked in" (people that cannot communicate verbally due to almost complete paralysis). In the future, BCIs will fundamentally change how we interact with devices, for example, making our mobile phones a true extension of ourselves; BCIs could let us control games with our minds, producing truly immersive experiences; and there are a multitude of healthcare related applications in stroke rehabilitation, epilepsy treatment, sleeping disorders and even Alzheimer's treatment.

The games industry could be an initial route to market for some wearable neurotechnology devices. Moreover, by gathering data from a large user base (something very difficult to do currently for clinical EEG trials), new knowledge will be generated which could be fed back into the creation of better medical devices. Further, by involving the games industry, it could be possible to make neurodisability rehabilitation more fun (a big problem with current rehabilitation regimes is their monotony which limits the time people are prepared to spend working on rehabilitation).

[7] https://aabme.asme.org/posts/wireless-implant-helps-paraplegics-walk-again

[8] Flesher, Sharlene, et al. "Intracortical microstimulation as a feedback source for brain-computer interface users." Brain-computer interface research. Springer, Cham, 2017. 43-54.

[9] Wong, Joshua K., et al. "STN vs. GPi deep brain stimulation for tremor suppression in Parkinson disease: a systematic review and meta-analysis." *Parkinsonism & related disorders* 58 (2019): 56-62.

[10] Fisher, Robert S., and Ana Luisa Velasco. "Electrical brain stimulation for epilepsy." *Nature Reviews Neurology* 10.5 (2014): 261-270.

[11] Aldehri, Majed, et al. "Deep brain stimulation for Alzheimer's Disease: An update." *Surgical neurology international* 9 (2018).

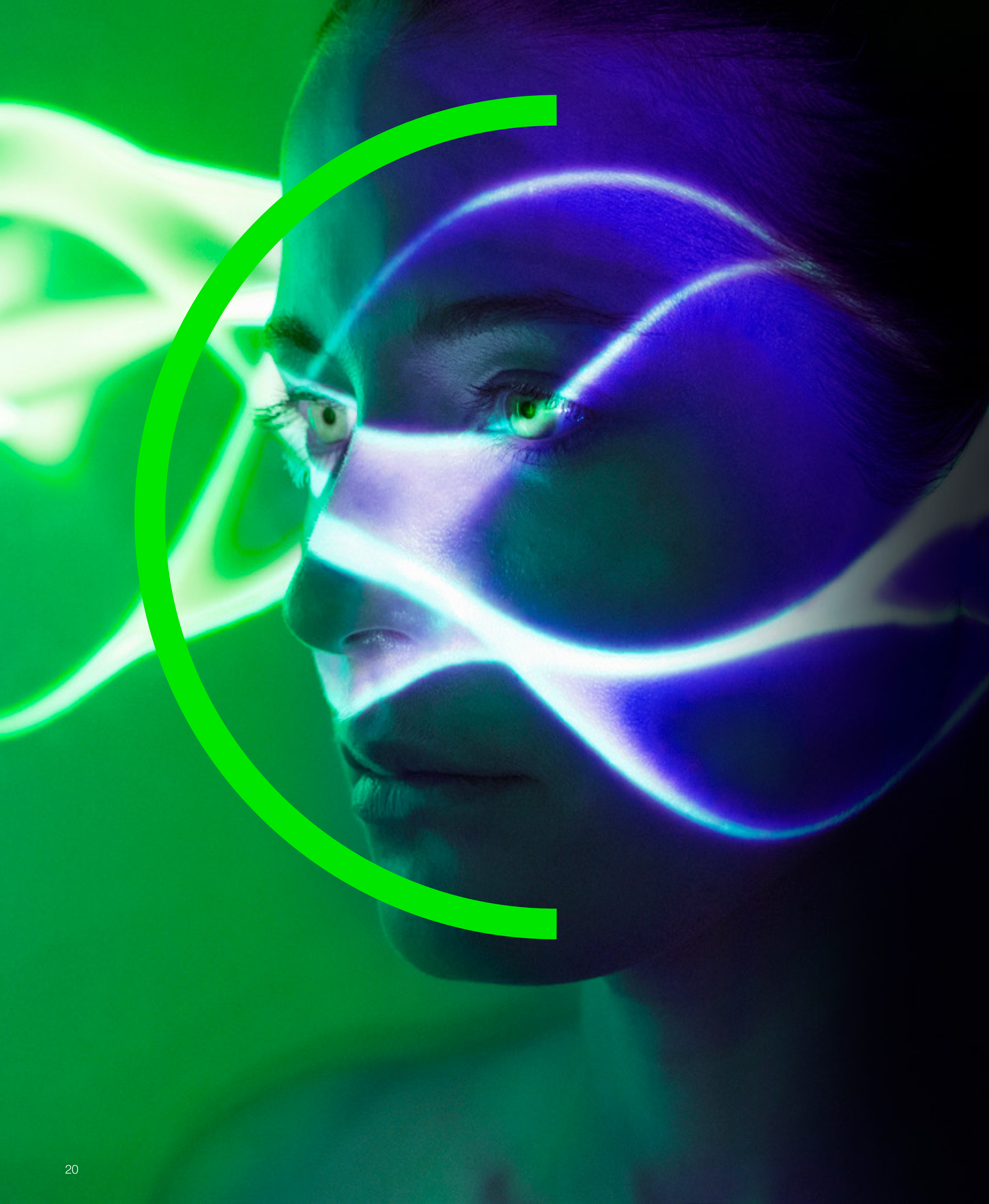
[12] https://www.alpha-stim.com/blog/nhs-study-of-alpha-stim-for-anxiety-can-revolutionize-mental-health-care-in-the-uk/

[13] https://www.versusarthritis.org/media/2071/working-with-arthritis-policy-report.pdf

[14] https://www.abpi.org.uk/media/1679/raising_game.pdf

[15] https://www.versusarthritis.org/media/14594/state-of-musculoskeletal-health-2019.pdf

[16] https://www.nras.org.uk/nerve-stimulation-study-shows-potential



Human Cognitive Augmentation

Neurotechnology will enable human cognitive enhancement. Neurostimulation has already been shown to improve perception, learning, memory and decision making[17].

Collaborative BCIs, where the information from several users is combined has been shown to improve the speed and accuracy of decision making when compared to the average human[18].

Early studies have also demonstrated that direct brain-to-brain interfacing is possible, whereby the intention from one subject is recognised by an EEG-based BCI, which then triggers a signal that is sent out to a second subject using transcranial magnetic stimulation to induce hand motion or even consciously transmit a word[19]. A closed loop system can be achieved by introducing muscle-to-muscle interfacing through electromyography and functional electrical stimulation.

Another important application of BCIs is symbiotic human-machine interactions using closed-loop systems which will allow Human-Machine Teaming (HUMAT). Neuroadaptive systems automatically adapt to their operator's mindset through the real-time analysis of brain activity[20]. Flexible and adaptive machines that can "intelligently anticipate a teammate's capabilities, intentions and generalise specific learning experiences and enable true human-machine teaming" is potentially achievable within 10-20 years[21]. There are likely to be important military applications for HUMAT; a Joint Concept Note 1/18 for the MOD states that "the impacts (of AI and robotics) on conflict are a matter of when, not if[22]."

[17] Coffman, Brian A., Vincent P. Clark, and Raja Parasuraman. "Battery powered thought: enhancement of attention, learning, and memory in healthy adults using transcranial direct current stimulation." *Neuroimage* 85 (2014): 895-908.

[18] Cinel, Caterina, Davide Valeriani, and Riccardo Poli. "Neurotechnologies for human cognitive augmentation: current state of the art and future prospects." Frontiers in human neuroscience 13 (2019): 13.

[19] Mashat, M. Ebrahim M., Guangye Li, and Dingguo Zhang. "Human-to-human closed-loop control based on brain-to-brain interface and muscle-to-muscle interface." *Scientific reports* 7.1 (2017): 1-11.

[20] Zander, Thorsten O., et al. "Neuroadaptive technology enables implicit cursor control based on medial prefrontal cortex activity." *Proceedings of the National Academy of Sciences* 113.52 (2016): 14898-14903.

[21] https://basicresearch.defense.gov/Portals/61/Future%20Directions%20in%20Human%20Machine%20Teaming%20Workshop%20report%20%20%28for%20public%20release%29.pdf

[22] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/709359/20180517-concepts_uk_human_machine_teaming_jcn_1_18.pdf

Towards a UK Neurotechnology Strategy

Development of New Neurotechnologies Provides Non-Pharmaceutical Alternatives to Chronic Pain Relief

Imagine never being able to hug your loved ones because of chronic, excruciating pain. This was the case for Joan who suffered severe neuropathic pain for over 6 years after a Schwannoma (a nerve sheath tumour) was removed from around her brachial plexus. The entire right side of her upper body became incredibly sensitive to touch, where even light touch or clothes brushing against her skin could leave her in agonising pain.

After a number of unsuccessful visits to different consultants, Joan met Dr Tacson Fernandez, Clinical Lead for the Neuromodulation Service at the Royal National Orthopaedic Hospital. He identified Joan's pain as neuropathic and secondary to changes in the brachial plexus, a network of nerves that sends signals from the spinal cord to the shoulder, arm and hand. Dr Fernandez implanted peripheral nerve stimulators which covered the chest wall area of pain. He also implanted a spinal cord stimulator, which covered the entire distribution of the brachial plexus on the painful side and also targeted the facial sensitivity. Within days of the surgery, Joan was able to hug her husband for the first time in 6 years. The pain she experienced for years was finally more manageable.

Dr Fernandez commented, *"Neuropathic pain is a severe, debilitating type of nerve pain which is often difficult to manage using conventional treatment options and dramatically affects the quality of life of sufferers. Some effective interventions such as spinal cord stimulators are currently available, but it is vital that more treatments are developed that can effectively target and treat the range of issues that neuropathic pain presents with."*

Neuropathic pain can result from a number of ailments such as multiple sclerosis, spinal cord injury or a stroke. Diabetes, infection, chemotherapy, some surgeries and alcoholism can also result in painful metabolic peripheral neuropathies. The pain is often described as a burning, shooting, electric shock like sensation. This excruciating pain can be triggered by mechanical or thermal stimuli which substantially impairs quality of life.

Regular painkillers such as ibuprofen and paracetamol are generally not effective; specific nerve pain-killers such as anti-epileptics, anti-depressants or opioids are sometimes used but have numerous side effects and might only prove beneficial in one out of four patients.

There is a growing interest in non-pharmaceutical alternatives to manage neuropathic pain. Spinal cord stimulation has been in use for over three decades, is relatively safe, reversible and a cost-effective long-term solution to manage neuropathic pain. Newer high frequency devices also provide paraesthesia-free stimulation. Brain computer interfaces can provide neurofeedback for the treatment of central neuropathic pain following injuries to the spinal cord. Recently, there has also been promising developments in visual feedback therapies which use virtual and augmented reality, optogenetics, transcranial magnetic stimulation techniques etc., to help with pain management for patients with spinal cord injury.

Neurofeedback (NFB), a non-invasive treatment, utilises brain computer interface technology that provides analysis and visualisation of brain activity in real time, while the person is engaged in an NFB task. NFB is typically based on electroencephalography (EEG) due to its technical features, size and affordable price.

NFB is a neuromodulatory technique that enables voluntary modulation of brain activity in order to treat neurological conditions, such as attention deficit hyperactivity disorder, insomnia, depression epilepsy and chronic pain. A distinctive feature of this technique is that it actively involves participants in the therapy. It is believed that NFB tunes brain oscillations towards a homeostatic set-point which affords an optimal balance between network flexibility and stability (i.e. self-organising criticality).

Dr Aleksandra Vuckovic from the University of Glasgow has developed an NFB protocol for treatment of Central Neuropathic Pain (CNP). The protocol is based on modulation of brain activity in selected frequency bands, from the motor cortex. A recent study showed that, out of 15 patients, 75% reported statistically significant reduction of pain, and pain relief was clinically significant (larger than 30%) in 53% participants[23].

A half an hour NFB session provided pain relief that lasted from several hours to 2-3 days.

Prolonged use of NFB may modify baseline brain activity in a desired direction. In addition, long term users can learn how to apply NFB mental strategy even without an NFB device (transfer learning) thereby achieving similar effect as with real NFB. Apart from the occasional headache, there are no known side effects of NFB.
The development of new neurotechnologies will help treat the growing number of people who suffer from neuropathic pain. The KTN held a biodesign workshop in September 2019 to identify clinical unmet needs for neuropathic pain and discuss potential solutions. There are several, interconnected, high level needs which need to be met to improve patient outcomes:

- Better understanding of pain mechanisms and treatments
- Reduce infection rates for invasive systems
- Better non-invasive pain relief
- Better data and clinical/QALY evidence
- Better communication among stakeholders
- Reduce time to market

The full report can be found online[24], along with reports on stroke rehabilitation[25] and mood and psychotic disorders[26].

[23] Vuckovic, Aleksandra, et al. "EEG correlates of self-managed neurofeedback treatment of central neuropathic pain in chronic spinal cord injury." *Frontiers in neuroscience* 13 (2019): 762.

[24] https://admin.ktn-uk.co.uk/app/uploads/2020/03/Workshop-outcomes-document-for-neuropathic-pain-.pdf

[25] https://admin.ktn-uk.co.uk/app/uploads/2020/05/Workshop-outcomes-document-for-Stroke-Rehabilitation.pdf

[26] https://admin.ktn-uk.co.uk/app/uploads/2020/03/Workshop-outcomes-document-for-mood-and-psychotic-disorders.pdf

Overview of the UK Neurotechnology Landscape

The UK has a world leading research base in neurotechnology, covering areas such as fundamental neuroscience, medical imaging, bioelectronic medicines, brain-computer interfaces and neural prosthetics. Moreover, the UK has regional excellence across the country, for example, non-invasive neurotechnology in Northern Ireland, photonics in Scotland, dementia research in Wales, optogenetics in the north east of England, mental health in the Midlands and clinical, experimental and computational neuroscience in the South.

Furthermore, there is already significant collaboration between UK universities, for example, the £10m EPSRC and Wellcome Trust funded CANDO (Controlling Abnormal Network Dynamics using Optogenetics) project, a collaboration between Newcastle University, University College London, Imperial College London and the Newcastle Hospitals NHS Foundation Trust. However, to put this level of funding in perspective, a typical new neurotechnology implant costs about £100m to bring to market.

The UK is also training the next generation of neurotechnologists, for example, at the Centre for Doctoral Training in Neurotechnology at Imperial College London.

Neurotechnology is an incredibly multidisciplinary endeavour, covering areas as diverse as fundamental neuroscience, bioelectronic engineering, artificial intelligence and materials science. There are also a number of intellectual property and regulatory stages that need to be passed to get a new neurotechnology to market. It is likely, therefore, that many companies will not have all these areas covered in-house.

The UK has a growing pre-competitive landscape that can accelerate the commercialisation of new neurotechnologies:

- The Henry Royce Institute is the UK's national institute for advanced materials research and innovation and has expertise in new materials for bioelectronics;
- The new £5.2 million Wellcome Trust funded Manufacture of Active Implant and Surgical Instruments (MAISI) facility will open at the end of 2020. The facility, located at St Thomas' Hospital, addresses the lack of specialised and regulated manufacturing facilities for prototype development of Class II & III medical devices for first-in-patient studies in the UK. The initiative is a collaboration between King's College London, UCL and Newcastle University;
- The Centre for Process Innovation can help companies commercialise new wearable medical devices. Their expertise covers the entire development cycle, supporting companies from initial concept through to adoption of the device in healthcare;
- The Alan Turing Institute which has an Artificial Intelligence (AI) programme with the goals of advancing world class research into AI, its applications and its implications for society;
- The UK Dementia Research Institute, launched in 2017, is the single biggest investment the UK has ever made in dementia thanks to £290 million from founding funders the Medical Research Council (MRC), Alzheimer's Society and Alzheimer's Research UK. The institute carries out research relevant to all dementias, including Alzheimer's disease, Parkinson's disease, frontotemporal dementia, vascular dementia, Huntington's disease and beyond;
- NIHR MindTech is a national centre focusing on the development, adoption and evaluation of new technologies for mental healthcare and dementia.
- The Francis Crick Institute is dedicated to understanding the fundamental biology underlying health and disease. Their work is helping to understand why disease develops and to translate discoveries into new ways to prevent, diagnose and treat illnesses.

Towards a UK Neurotechnology Strategy

There are currently only a handful of large companies actively involved in neurotechnology in the UK. LivaNova is a UK headquartered medical device manufacturer. The company develops devices used for cardiac surgery and neuromodulation and has annual sales of over $1 billon. However, it should be noted that research and development for neuromodulation is predominantly carried out in Texas in the United States. An important activity of a UK neurotechnology programme must be to attract these types of jobs to the UK. Galvani Bioelectronics is a joint venture between GSK and Verily Life Sciences (an Alphabet company), who have invested £540 million over seven years to develop bioelectronic medicines, a new class of medicines consisting of miniaturised, implantable devices. It is important that the UK support the long-term vision of Galvani Bioelectronics with a well trained workforce and vibrant academic community. The UK also has a growing SME base in neurotechnology. A few examples of these companies include:

- **Bioinduction** are developing Picostim, a miniaturised brain pacemaker, which is small enough to be skull-mounted and could help treat diseases of cerebrovascular origins such as resistant hypertension, stroke, Alzheimer's disease and vascular dementia;
- **BIOS Health** are developing a full-stack neural interface platform, that uses AI to decode and encode the signals from the brain to the body, to treat chronic health conditions;
- **BrainWaveBank** has developed a convenient EEG headset to track brain activity and measure cognitive performance;
- **Finetech Medical** is a specialist manufacturer of implanted functional neuro-stimulators and has one of the few facilities available in Europe for the manufacture of Class III active implanted medical devices;
- **Magstim** is a leading supplier of Transcranial Magnetic Stimulation (TMS) stimulators, an effective, non-invasive outpatient treatment for depression;
- **NeuroCONCISE** has developed FlexEEG, an electroencephalography device that provides a unique pairing of unobtrusive, high-precision, wearable electronics, in a slim, low-profile flexible case that can be embedded and concealed in any stylish headwear and seamlessly connected with their AI-enabled software and the cloud for brain-computer interfacing (BCI), neurofeedback, brain monitoring, medical and neuroscience research, recreation, gaming and sport, among others;
- **Neurovalens** has designed cranial nerve stimulation technology that accurately and efficiently activates key brainstem neurons without needing implanted electrodes.

The KTN has created an online version of the UK Neurotechnology Landscape which details many of the UK's neurotechnology organisations[27].

Although neurotechnology is an emerging industry, the UK has a strong value chain in supportive technologies such as sensors, flexible electronics, artificial intelligence and advanced materials which will supply much of the coming neurotechnology sector. These should act as an anchor for neurotechnology companies in the UK. The UK's expertise in pharmaceuticals will be a strong source of expertise in commercialising medical products while the creative sector and especially the UK's games industry should offer an initial route to market for brain-computer interfaces.

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[27] www.ktn-uk.org/programme/neurotechnology-landscape

The UK has the opportunity to be home to a new generation of technology companies.

Opportunities for the UK

During the early years of the internet (in which ARPA, the predecessor of DARPA, played a central role in its development), it would have been hard to imagine some of its present-day applications. In the same way it is difficult to foresee the full impact neurotechnology might have in the future, but new platform technologies that can make use of neural data and link human brains to artificial intelligence[28] are likely to have an enormous economical and societal impact.

No country yet has an unassailable lead in neurotechnology, however, 'Big Tech' (e.g. Google, Amazon, Facebook, Apple, Microsoft, Tencent, Alibaba) and governments across the world, especially in the EU, US and China, are investing considerable amounts of money into its development[29] [30].

With the emergence of new neural interface technologies, the UK has the opportunity to be home to a new generation of technology companies. In order to achieve this aspiration, significant investment is needed to develop and grow a UK ecosystem for neurotechnology. Moreover, by ensuring that the UK has a competitive neurotechnology sector, it will have an active role in the development of new international frameworks in ethics, regulations and data security.

The importance of this is cast into sharper focus when considering some of the possible risks associated with neurotechnology, such as thoughts and emotions being monitored or even manipulated by companies, governments or others[31] [32] [33].

The recent decision to remove all Huawei equipment from UK 5G networks by 2027 demonstrates the government's commitment to protect the UK's data from external threats. It is essential that that the government takes an early lead in safeguarding neural data. The Royal Society's iHuman report sets out a series of recommendations around the use and protection of neural data[31].

With the development of neurotechnology accelerating across the world, the UK has an exciting opportunity to help shape the development of a new wave of technologies, but the sector needs support now for this to become a reality.

[28] https://www.forbes.com/sites/alexknapp/2019/07/17/elon-musk-sees-his-neuralink-merging-your-brain-with-ai/#433ec70c4b07
[29] http://www.unesco.org/new/en/natural-sciences/science-technology/single-view-sc-policy/news/brain_research_has_become_a_policy_focus_for_china/
[30] https://nsiteam.com/social/wp-content/uploads/2019/10/SMA-Chinese-Strategic-Intentions-White-Paper-FINAL-01-Nov-2.pdf
[31] https://www.scmp.com/news/china/society/article/2143899/forget-facebook-leak-china-mining-data-directly-workers-brains
[32] https://royalsociety.org/-/media/policy/projects/ihuman/report-neural-interfaces.pdf
[33] DeFranco, Joseph, Diane DiEuliis, and James Giordano. "Redefining Neuroweapons." *PRISM* 8.3 (2019): 48-63.

Steering Group

A steering group has been formed to help guide the creation of a UK Neurotechnology Strategy. The first meeting will take place on the 3rd September 2020.

Prof. Keith Mathieson (Chair):
Royal Academy of Engineering Chair in Emerging Technologies and Director of the Institute of Photonics, where his team develops neural interface systems to further the understanding of brain circuits and develop implantable devices to restore function.

Prof. Tim Denison (Co-chair):
Royal Academy of Engineering Chair in Emerging Technologies with a joint appointment in Engineering Science and Clinical Neurosciences at the University of Oxford, where he explores the fundamentals of physiologic closed-loop systems. He is also Programme Leader, Bioengineering, at the MRC Brain Network Dynamic Unit.

Dr. Valerie Voon:
Senior Principle Investigator, Neuropsychiatrist and MRC Senior Clinical Fellow with the Department of Psychiatry at the University of Cambridge. Currently president of the British Neuropsychiatry Association.

Dr. Tacson Fernandez:
Consultant in Interventional Chronic Pain Medicine, Acute Pain management and Anaesthesia at the Royal National Orthopaedic Hospital, London.

Dr. Tim Constandinou:
Leads the Next Generation Neural Implants lab at Imperial College London and is Deputy Director of the Centre for Bio-inspired Technology.

Prof. Damien Coyle:
Professor of Neurotechnology and currently Director of the Intelligent Systems Research Centre and Research Director in the School of Computing, Engineering and Intelligent Systems at Ulster University.

Dr. Chris Pomfrett:
Clinical Scientist, Technical Adviser - Research Commissioning, National Institute for Health and Care Excellence (NICE).

Annalise Whittaker:
Human Systems Group at the Defence Science and Technology Laboratory (Dstl).

Dr Lothar Krinke:
Chief Executive Officer of Magstim.

Dr Eric Chow:
Senior Director, Product Development at LivaNova.

Ivor Gillbe:
Chief Executive Officer of Bioinduction.

Dr. Charlie Winkworth-Smith:
Knowledge Transfer Manager in the Emerging Technologies team at KTN and leads the Neurotechnology Innovation Network.

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