BRAIN MIND

BCI UNIVERSE

A mind map of sensing and stimulating brain technologies*

NONINVASIVE

INVASIVE

MEG

Magneto-Electroencephalography

1000s of patients/yr

A technique that uses magnetometers and gradiometers to amplify and record electromagnetic fields created by large groups of neurons. SQUID-MEG (conventional MEG) requires superconducting elements in a supercooled environment. Optically-Pumped MEG (OP-MEG) and other atomic magnetometers sense magnetic fields at "room temperature."

Major Applications:

- SQUID-MEG:
  - Epilepsy
  - Stroke
  - TBI
- OP-MEG:
  - Sleep and concentration studies
  - Consumer use for arousal, attention, emotion, learning, memory

- No surgery required
- High spatial resolution
- High temporal resolution
- OP-MEG is portable and relatively inexpensive
- Requires nested, magnetically shielded rooms (SQUID-MEG)
- Lower sensitivity to deep structures and gyral sources
- Few hospitals have available

EEG

Electroencephalography

10s of millions patients + consumers

Noninvasive, low spatial resolution technique used for recording cortical activity from an array of electrodes placed extracranially via neuroimaging or via portable devices. EEG measures several bands of neural oscillations (delta, theta, alpha, beta, gamma, and mu waveforms) to observe regional brain activity in real time.

Major Applications:

- ADHD
- ALS
- Chronic pain
- Computer control
- Consumer wellness
- Electrooculography
- Epilepsy
- Sleep disorders
- Stroke rehabilitation
- Widely used in diagnostics and monitoring

- Well-established tech
- No surgery required
- Inexpensive
- Portable + Wearable
- High temporal resolution
- Most funded sector, recent influx of private R&D funding
- Low signal/noise ratio (greatly improved with machine learning)
- Lower spatial resolution than MEG and fMRI
- Lower sensitivity to sulcal sources

ECoG

Electrocorticography

~100,000 patients

An invasive, high-throughput technique for measuring neuronal activity with a patch or strip of electrodes applied directly on the brain's surface. ECoG measures synchronized postsynaptic action potentials from large populations of cortical pyramidal neurons.

Major Applications:

- Epilepsy diagnostics
- Speech and movement synthesis from neural decoding
- Spinal cord injury
- Locked-in Syndrome
- Movement disorders

- High spatial coverage vs other implantables
- High spatial resolution
- Higher material longevity
- Less likely to produce strong immune response (does not penetrate brain tissue)
- Requires craniotomy
- Bulky wired connection and exposed cortex limits research applications
- Wireless implantable arrays only recently available

DBS

Deep Brain Stimulation

~200,000 patients

An invasive technique that modulates brain activity with surgically implanted electrodes embedded deep in the brain. DBS electrodes monitor neural activity and deliver electrical impulses, usually to the globus pallidus, nucleus ventralis intermedius thalami, or subthalamic nucleus.

Major Applications:

- Chronic pain
- Cluster headache
- Dystonia
- Epilepsy
- Essential tremor
- OCD
- Huntington's
- Major depression
- MS
- Parkinson's
- Substance Abuse
- TBI

- Many promising clinical applications in trials
- Improved electrode materials
- More surgeons familiar with implantation process
- Relatively mature manufacturer ecosystem
- Requires craniotomy
- Penetrates brain tissue
- Mental health side-effects for many
- Material longevity challenges

fMRI

Functional Magnetic Resonance Imaging

~200,000 patients

Imaging technique that uses magnetic fields to detect changes in cerebral blood flow as a marker for brain activity. Specifically, fMRI measures deoxygenated to oxygenated blood ratio in the brain (which have different magnetic susceptibility) to identify neurons that are firing (active neurons consume more oxygen), revealing which structures of the brain are active at a given moment in time.

Major Applications:

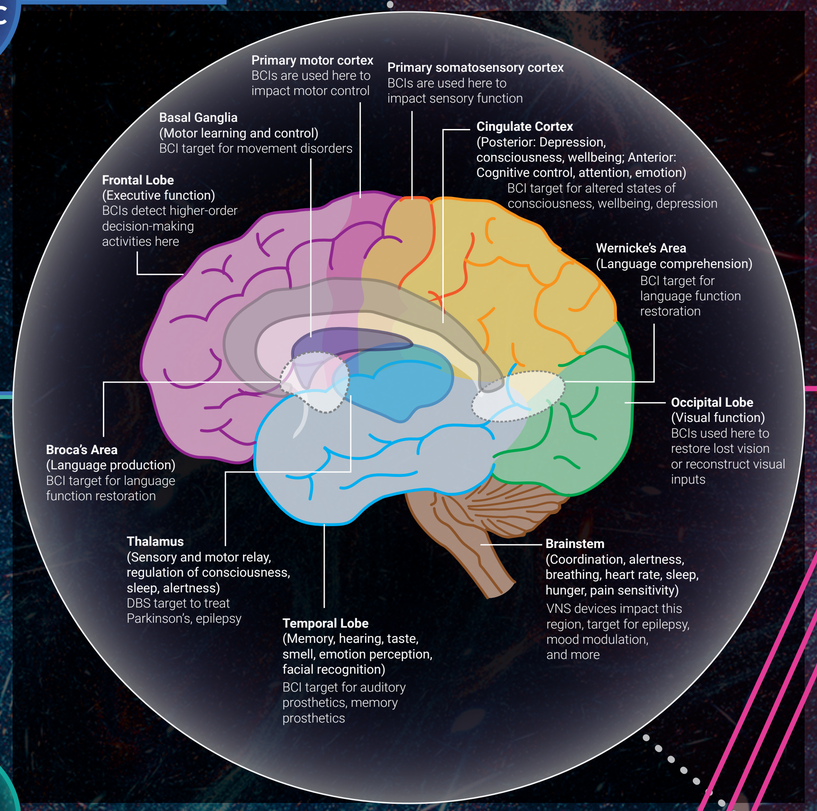
- Bipolar disorder
- Brain tumors
- Chronic pain
- Epilepsy
- Major depression
- Memory studies
- Schizophrenia
- Widely used in diagnostics and monitoring

- No surgery required
- High spatial resolution
- Real-time reading
- Ability to do behavioral analysis
- Large form factor
- Low temporal resolution
- Proxy measure for neuronal activity

ELECTRO-MAGNETIC

BRAIN SENSING

BRAIN STIMULATING



Implanted Microelectrodes

Tiny electrodes (thickness under 50 µm) delivered via craniotomy, used in electrophysiology for recording neural signals and/or stimulating the brain.

1,000s of patients

Major Applications:

- ALS
- Blindness/ocular injury
- Epilepsy
- Locked-in Syndrome
- Movement disorders
- OCD
- Peripheral nerve injury
- Spinal cord injury
- Stroke

- Recent influx of private R&D funding
- High spatial resolution
- High signal/noise ratio
- Many potential prosthetics applications
- Portable
- Lower surgical risk than ECoG, DBS
- Requires craniotomy
- Penetrates brain tissue
- Low material longevity

fNIRS

Functional Near-Infrared Spectroscopy

~10,000 patients

A neuroimaging technique that measures hemoglobin concentration in specific brain regions using a near-infrared light source (~650-1000 nm) and a detector that measures photon signal intensity. Blood oxygenation alters the signal and this fluctuation is used as a biomarker for brain activity.

Major Applications:

- Deafness
- Depression
- Mental arithmetic
- Motor execution
- Motor imagery
- Music imagery
- Stroke
- TBI

- Noninvasive
- Inexpensive
- Portable
- Multi-channel systems
- Slow information transfer rate
- High error rate
- Proxy measure for neuronal activity

EE

Endovascular Electrodes

1 implanted patient in 2020

A miniature mounted electrode array that is passed intravenously into the cerebral vasculature and placed in close proximity to specific brain regions.

Major Applications:

- Restoring voluntary motor impulses to control digital devices in patients with severe paralysis

- Can be implanted in many different locations
- Can acquire vascular ECoG signals
- >6 month biocompatibility in animal brain blood vessels
- Requires minimally invasive surgery
- Requires lifelong anticoagulant use
- Can only record from neurons adjacent to large vessels

METABOLIC

Optogenetics

A stimulation method that can activate preselected neurons and circuits using light. Targeted cell types are genetically modified to produce light-sensitive proteins called opsins. These proteins trigger action potentials when the targeted cells are exposed to a specific wavelength of blue light.

Not yet used in humans

Major Applications:

- Neural circuit research
- Reversible disease models
- Structure-function mapping
- Vision restoration

- Specific cell type targeting
- Precise, bidirectional control of neurons
- High spatial and temporal resolution
- Widely used novel research tool
- Animal research only in foreseeable future

This is a living document.
See updated version at:
brainmind.org/bci

fTCD/tFUS

in trials only

Focused Transcranial Doppler/ Transcranial Focused Ultrasound Stimulation

fTCD is an imaging technique that uses a probe to transmit ultrasound pulses into the brain to determine velocity changes in blood flow that may correspond to neural activation. tFUS delivers low-intensity pulsed ultrasonic waves to the brain to directly modulate specific neuronal pathways. tFUS should be distinguished from high-intensity ultrasound, which is ablative.

Major Applications:

fTCD:
- Alzheimer's
- Cerebrovascular disorders
- Language, face and color processing, intelligence studies
- Tobacco dependence

tFUS:
- ALS
- Anxiety
- Coma recovery
- Essential Tremor/Parkinson's
- Depression
- Mild cognitive impairment

- Noninvasive
- High spatial resolution
- Reaches deep brain regions
- Inherent imaging capabilities
- Compatible with MRI and EEG
- Adaptable for closed-loop therapies
- Many promising clinical applications in trials
- Competing theories for mode of action
- fTCD: measurements may not correspond to neural activity
- Long-term effects not well established

tES (tACS, tDCS)

Transcranial Electrical (AC or DC) Stimulation

~1000 patients

Noninvasive, portable, electrical neurostimulators that produce long-lasting brain activity changes. A large electrode on a wearable device is placed above the targeted brain region. tACS applies a sinusoidal current to trigger action potentials, while tDCS uses a direct current to control activity of active neurons. Both modalities are applied at low intensities (1-2 mA) which should be distinguished from high-intensity methods like electroconvulsive therapy (ECT). Efficacy is often determined by behavioral changes.

Major Applications:

- Amblyopia
- Alzheimer's
- Consumer DIY kits
- Epilepsy
- Intraoperative imaging
- Major depression
- Mild TBI
- Parkinson's
- Stroke
- Sleep
- Substance abuse

- Noninvasive stimulation
- Portable
- Easy to use
- Many promising clinical applications in trials
- Relatively mature manufacturer ecosystem
- Competing theories for mode of action
- Only a fraction of the applied current reaches the brain
- High potential for misuse (recreational or unsupervised medical use)
- Long-term effects not well established

rTMS

Repetitive Transcranial Magnetic Stimulation

~30,000 patients

Noninvasive neurostimulation technique that uses a wire coil to produce a magnetic field that penetrates through the skull. The magnetic field induces small electrical currents that stimulate targeted areas of the brain under the coil.

Major Applications:

- Auditory hallucination
- Borderline personality disorder
- Bipolar disorder
- Major depression
- OCD
- Parkinson's
- PTSD
- Schizophrenia
- Smoking cessation
- TBI

- Noninvasive stimulation
- Many promising clinical applications in trials
- Adaptable for closed-loop applications
- Relatively mature manufacturer ecosystem
- Non-portable
- Low spatial resolution
- Physical side effects (short term)
- Requires regular clinic visits
- Small risk of induced seizure (<0.1%)

VNS

Vagus Nerve Stimulation
Noninvasive: tVNS or nVNS

~100,000 patients

Device that delivers electrical impulses to the vagus nerve via an implanted electrode or a noninvasive wearable clip or handheld device. VNS alters levels of neurotransmitters such as serotonin, norepinephrine, GABA, and glutamate (all brain chemicals that affect mood). The amount of stimulation is set by a magnetic wand by a doctor or adjusted by the patient in the case of nVNS/tVNS.

Major Applications:

- Alzheimer's
- Cancer
- Chronic pain
- Depression
- Epilepsy
- Migraines
- Parkinson's
- PTSD
- Stroke

- Has effective noninvasive options
- Recent influx of private R&D funding
- Well tolerated side effects which are easily mitigated
- Many promising clinical applications in trials
- Infection risk during implantation of invasive VNS
- Chance of pulse generator becoming displaced

*Our report focuses on BCIs with near-term potential for closed-loop applications. Technologies which do not directly read or stimulate the brain (EMG, haptics) and those which are not commonly used as a BCI (PET, microwave technology) are excluded.

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