Introduction to Neural Engineering

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What is neuroengineering (neurotechnology)?

- Neuroengineering is the confluence of neuroscience, device development, computation, and mathematics, and is one of the most exciting new ventures in science and technology today. Neuroengineering brings together state-of-the-art technologies, algorithms, experimental research and concepts that can:
  - Develop devices and computing to assist those with neural disorders – an issue that confronts nearly 1 billion people worldwide.
  - Reveal how computations are done by neural systems– one of the greatest challenges facing science today.
  - Inspire new algorithms, technologies, mathematics, and robotics via reverse engineering living neural systems.
  - Educate the next generation of scientists and engineers who will transcend the traditional boundaries of science, technology, engineering and mathematics.

Core Questions

- What is neural engineering?
- Why do we want to do neural engineering?
- Who benefits from this work?
- What do we need to know about the brain and body in order to do neural engineering right?
- What can neural engineering do that can't be done with other forms of treatment?

Main Fields of the Neural Engineering

- Neuroimaging (understand the brain)
- Neuromodulation/Neurostimulation (do stuff to the brain, Brain cell threaphy)
- Brain-Computer Interfaces (do stuff with the brain)

WHY NEUROENGINEERING(NEUROTECH)?

1. ***save lives***
   - neurological disorders caused approx. 9 million deaths worldwide in 2016[1]
   - second leading cause of death, after cardiovascular disease[1]
2. ***understand the human body's most complex organ***
   - "If everything you need to know about the brain is a mile, how far have we walked in this mile? 3 inches." ~ Jeff Lichtman, MCB professor @ Harvard University[2]
3. ***transhumanism***
   enhance human intellect, physiology, and capabilities
   - hard to fall a sleep
   - hard to focus for a long time

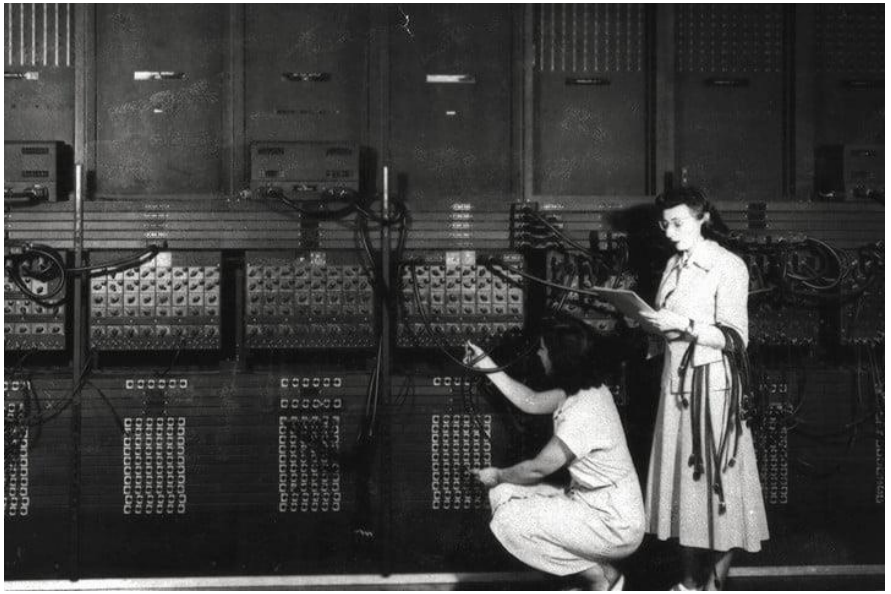
[1] GBD 2016 Neurology Collaborators. Global, regional, and national burden of neurological disorders, 1990-2016: a systematic analysis for the Global Burden of Disease Study 2016. Lancet Neurol. 2019 May;18(5):459-480. doi: 10.1016/S1474-4422(18)30499-X. Epub 2019 Mar 14. PMID: 30879893; PMCID: PMC6459001.
[2] https://www.youtube.com/watch?v=nvXuq9jRWKE

Mind Control - the half-life of technology intimacy

(source: Josh Wolfe, LUX Capital)

~75 years ago

- room-sized computers
- operated by researchers only



***ENIAC*, first electronic general-purpose computer**

Mind Control - the half-life of technology intimacy

(source: Josh Wolfe, LUX Capital)

~40 years ago

- desktops
- hands over keyboards

***APPLE MACINTOSH*, released 1984**

Mind Control - the half-life of technology intimacy

(source: Josh Wolfe, LUX Capital)

~30 years ago

- laptops
- combination of computer, keyboard, and mouse

1989 – Macintosh Portable

1991 – Powerbook 100

Mind Control - the half-life of technology intimacy

(source: Josh Wolfe, LUX Capital)

~15 years ago

- smartphones
- swiping, tapping, pinching
- on our bodies at all times, only separated by the fabric of our jeans

***iPHONE 1*, released 2007**

Mind Control - the half-life of technology intimacy

(source: Josh Wolfe, LUX Capital)

~7 years ago

- Smartwatches
- swiping, tapping, pinching
- always in contact with our skin
- sometimes worn at night

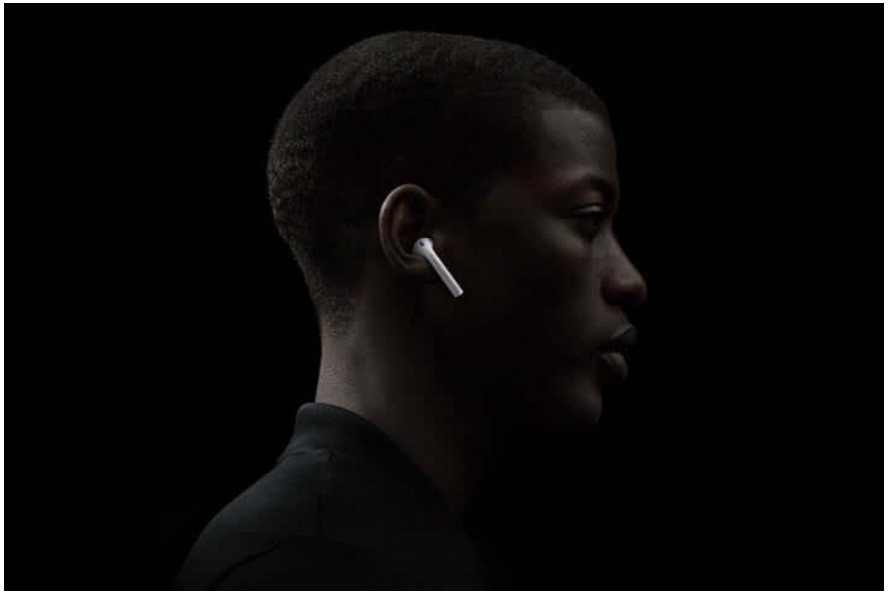
***iWATCH SERIES 1*, released 2015**

Mind Control - the half-life of technology intimacy

(source: Josh Wolfe, LUX Capital)

~5 years ago

- AirPods
- not just in our pockets, but in our ears



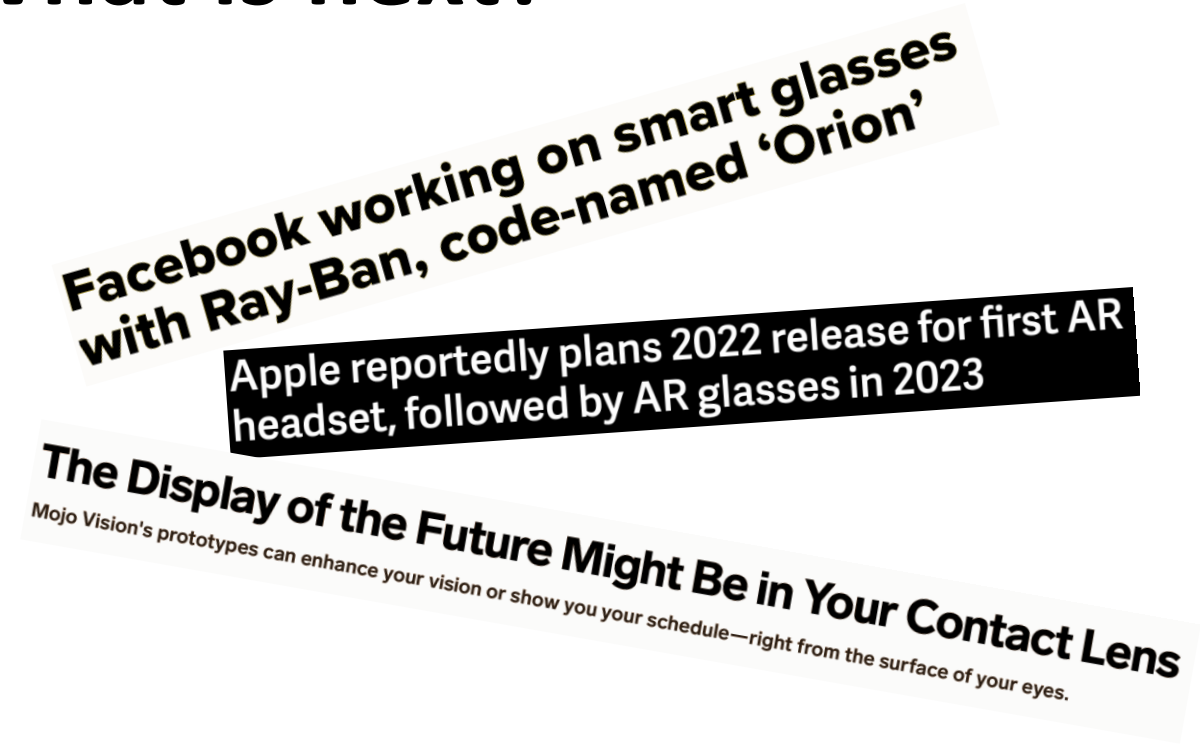
***AirPods 1*, released 2017**

What is next?

so what's next?

Heads Up Displays!

- Augmented Reality glasses
- Smart contact lenses



but how will we *control* these devices? how will we communicate our *intentions*?

What is next?

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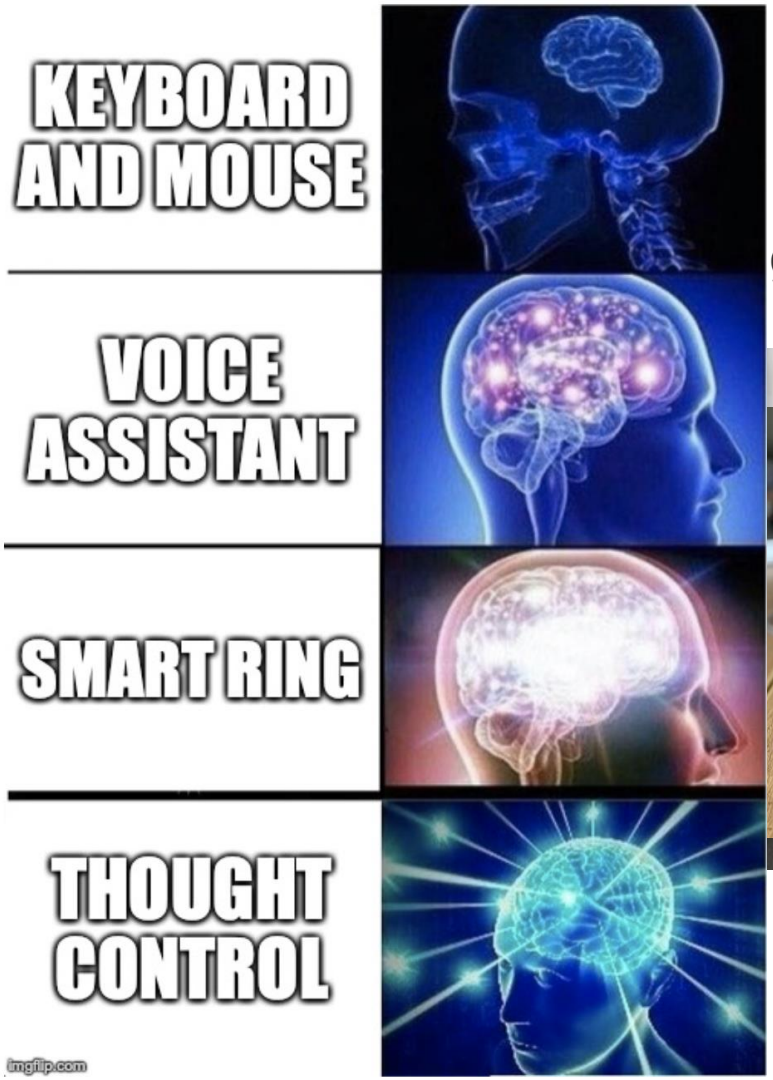
CAN WE GET RID



g that Would Work as a

ideas?

voice assistants

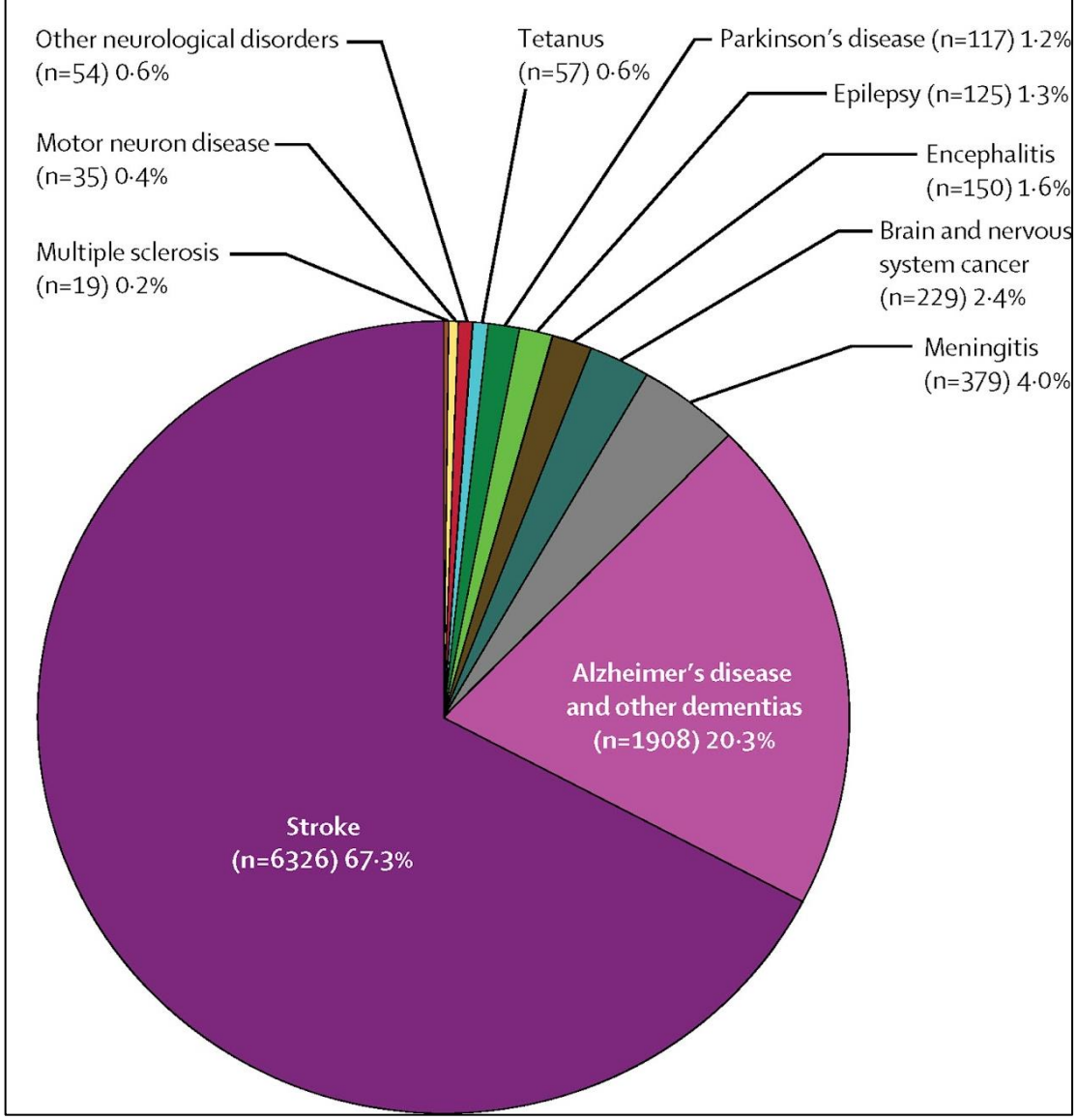
smart rings

WHY NEUROENGINEERING(NEUROTECH)?

- **Treat Neurological Disorders**
- **Understand the Brain**
- **Device Control**
- **Human Augmentation**

1. Treat Neurological Disorders

- neurological disorders caused approx. 9 million deaths worldwide in 2016[1]
- second leading cause of death, after cardiovascular disease[1]

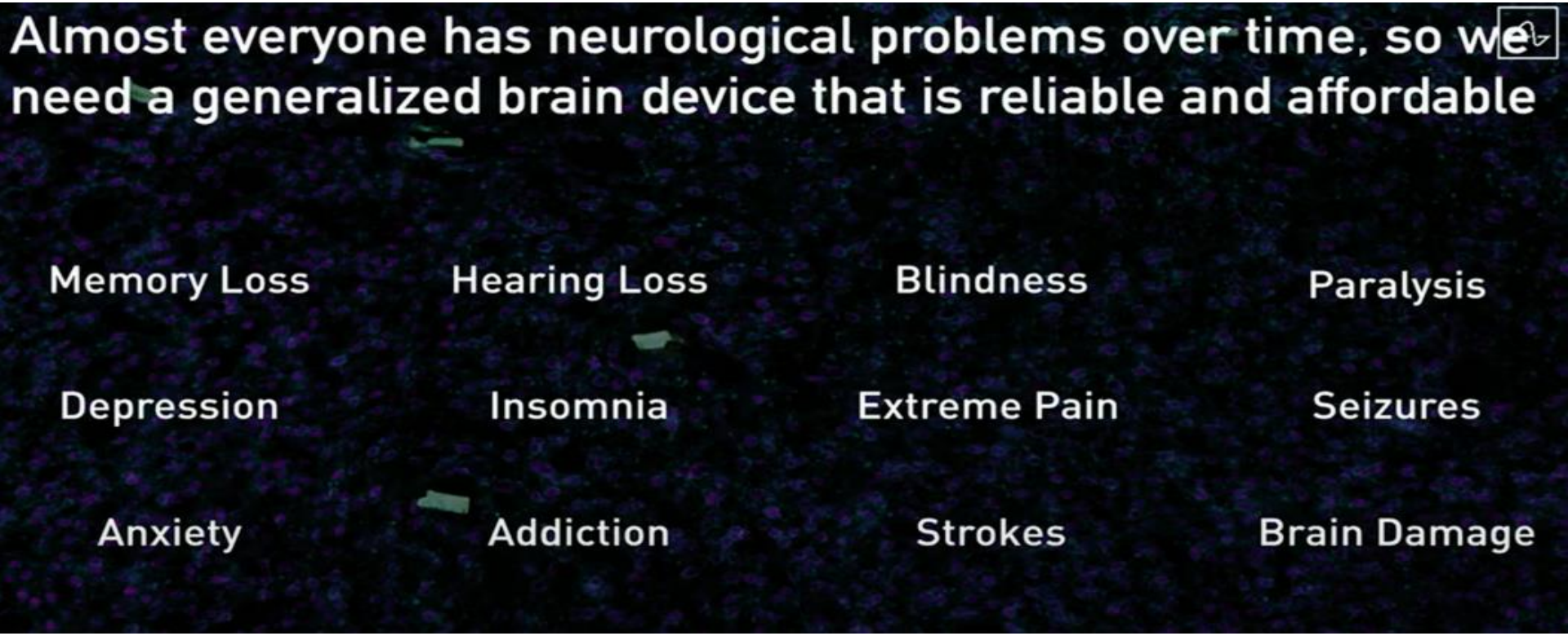


global 2015 deaths due to neurological disorders [2]

[1] GBD 2016 Neurology Collaborators. Global, regional, and national burden of neurological disorders, 1990-2016: a systematic analysis for the Global Burden of Disease Study 2016. Lancet Neurol. 2019 May;18(5):459-480. doi: 10.1016/S1474-4422(18)30499-X. Epub 2019 Mar 14. PMID: 30879893; PMCID: PMC6459001.

[2] Feigin, Valery L., et al. "Global, regional, and national burden of neurological disorders during 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015." *The Lancet Neurology* 16.11 (2017): 877-897.

Aim of Neuralink

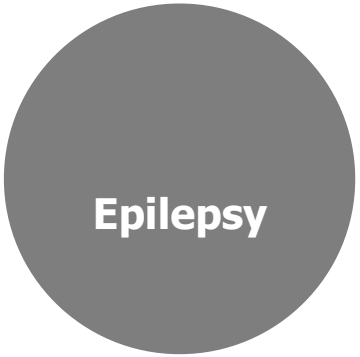


Source: Neuralink Progress Update, Summer 2020

EXAMPLES OF DISORDERS

- nerve cell damage in the **substantia nigra**
- cells in this region produce the neurotransmitter **dopamine**
- dopamine helps regulate movement
- **Deep Brain Stimulation:** placing thin wires in the brain that send electrical impulses to the basal ganglia to control motor impulses

- kills neural pathways and brain cells
- main symptoms: memory loss and confusion
- **MRI, CT, PET**: neuroimaging techniques to help detect and diagnose Alzheimer's
- **Transcranial Electromagnetic Treatment (TEMT):** non-invasively slows the progression of Alzheimer's



- sudden, recurrent episodes of sensory disturbance
- excessive brain cell activity
- **Electroencephalography (EEG):** go-to technology for diagnosis; doctors look for wave abnormalities
- **Vagus Nerve Stimulation (VNS):** popular treatment solution, device under chest that electrically stimulates vagus nerve in neck

STROKE REHABILITATION

STROKE FACTS[1]

- every 40 seconds, someone in the US has a stroke
- every 3.5 minutes, someone dies of stroke
- stroke is the leading cause of **long-term motor deficits** and **mobility reduction**

A PROMISING NEUROTECH SOLUTION

- *motor imagery*: mentally rehearsing a certain action
- detect imagined movements in EEG signals
- use detected movements to provide visual (games, VR) and mechanical feedback
- *the brain thinks the movement is actually being executed*

limiting factor: **nurse availability**

[1] https://www.cdc.gov/stroke/facts.htm

[2] Feigin, Valery L., et al. "Global, regional, and national burden of neurological disorders during 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015." *The Lancet Neurology* 16.11 (2017): 877-897.

Motor Imagery / Mental Practice – Strokengine

Commercial Solution - recoveriX

[High-Tech Stroke Therapy - recoverix.com]

[RecoveriX Stroke Rehabilitation System to Be Presented at Cybathlon - Fitness Gaming (fitness-gaming.com)]

Motor Imagery (MI)

Imagine a hand or a foot movement. recoveriX measures and analyses brain waves, which reflect the motor imagery and determines whether the motor imagery was correct.

Once motor imagery has been recognized, virtual reality and functional electrical stimulation will be activated.

The positive impacts

The responsible areas of the brain are activated by the motor imagery, which can facilitate brain plasticity. Unlike conventional physiotherapy, the BCI guarantees that actual movements only occur when people imagine the corresponding movement.

The simultaneous activation of relevant cortical areas and peripheral neurons encourages Hebbian learning.

Virtual Reality (VR)

The simulation on the screen makes motor imagery visible. Patients sit in front of a screen, where they see hands and feet of an avatar. This gives patients the feeling of watching their own movements in front of a mirror.

If recoveriX recognizes motor imagery of the movement (such as a right hand movement), the avatar moves the right hand.

The positive impacts

This real-time feedback is very easy to understand. If a patient imagines a movement, then the avatar performs the movement.

The experience is similar to watching yourself in a mirror. It can facilitate mirror neuron activation.

Electrical Stimulation (FES)

For this stimulation, two electrodes are placed (for example) on the dorsiflexors of the wrist or on the leg. If the system recognizes a correct motor imagery, the muscles get electrically stimulated, causing a real movement.

This should help you re-learn how to initiate movement, and thus make movement possible again.

The positive impacts

The patient receives clear, user-friendly feedback through active movement. Just imagine a movement, and you can see your body move accordingly.

The patient is motivated because the experience repeatedly reminds the patient of the desired goal: being able to move again.

2. Understand the Brain

- The Human body's most complex organ is brain.
- "If everything you need to know about the brain is a mile, how far have we walked in this mile? 3 inches." ~ Jeff Lichtman, MCB professor @ Harvard University[1]
- We still don't know enough about the brain.

[1] https://www.youtube.com/watch?v=nvXuq9jRWKE

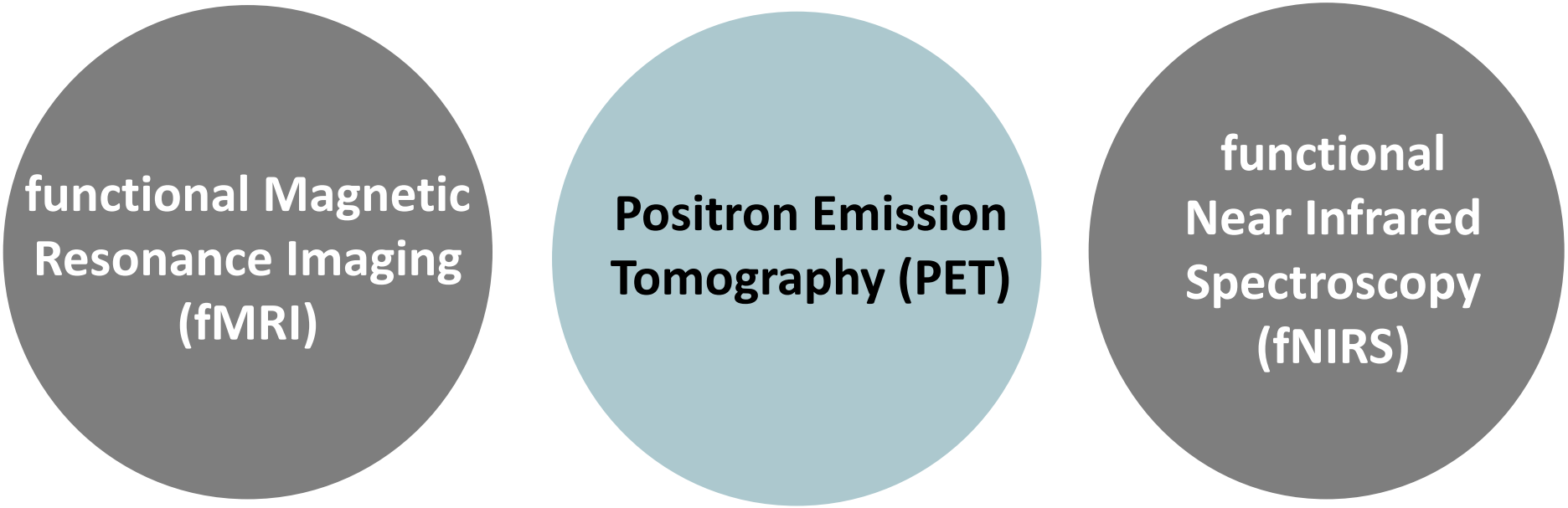
ELECTROPHYSIOLOGICAL NEUROIMAGING

- *directly* measure electrical activity of neurons
- *the two examples:*
  - **Electroencephalography** (EEG): records brain's electrical activity
  - **Magnetoencephalography** (MEG): records magnetic fields produced by brain's electrical activity
- both EEG and MEG are non-invasive
  → *no surgery required*

METABOLIC NEUROIMAGING

- **don't** *directly* measure brain's electrical activity (neurons firing), but rather *indirect* measures ("consequences") of this activity:
  - blood oxygenation levels
  - emissions of radioactive chemicals in bloodstream

METABOLIC NEUROIMAGING TECHNIQUES



blood oxygenation levels

radioactive emissions of chemicals in bloodstream

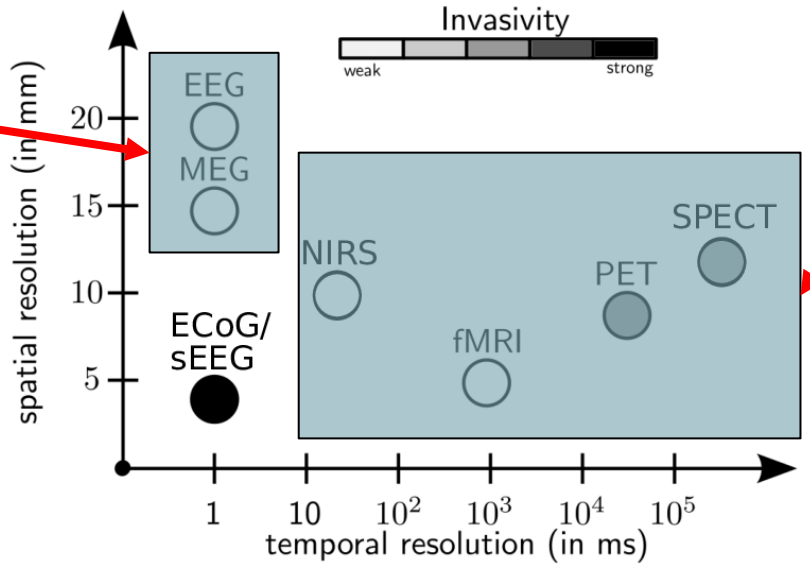
absorption of infrared light by hemoglobin

TEMPORAL AND SPATIAL RESOLUTION

ELECTROPHYSIOLOGICAL NEUROIMAGING: high temporal resolution, low spatial resolution

Why high temporal resolution? directly recording neuronal activity.

Why low spatial resolution? electrodes placed on scalp → can't pinpoint exact source of electrical activity



METABOLIC NEUROIMAGING: low temporal resolution, high spatial resolution

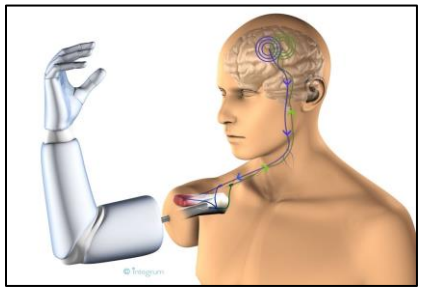
Why low temporal resolution? blood measuring (a consequence of neuronal activity, not the activity itself), so time delay (e.g. blood oxygenation levels take few seconds to rise)

Why high spatial resolution? → highly localized measurements of brain activation

TEMPORAL RESOLUTION: precision of measurements in relation to time

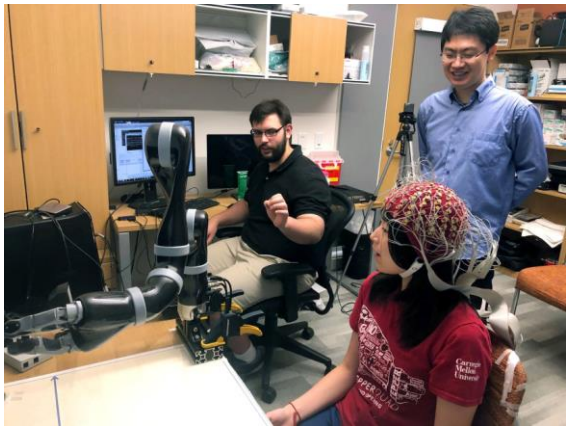
SPATIAL RESOLUTION: precision of measurements in relation to space

3. Device Control



MEDICAL	COMMERCIAL
Neuroprosthetics	Personal computer input (typing, scrolling)
Wheelchairs	Smart home appliances
Robotic Surgeons	Drones

MILO, Neurotech @ McGill's EEG controlled wheelchair



CMU's EEG controlled robotic arm, 2019

4. Human Enhancement

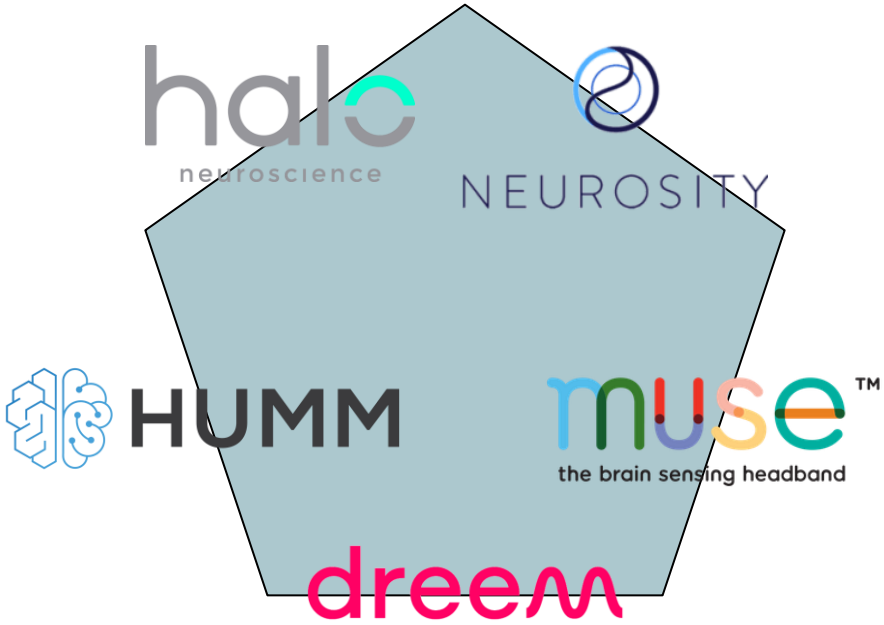
Sports: ***Halo***
Increasing strength, endurance, and muscle memory. **how?** tDCS to your motor cortex

Productivity: ***Neurosity***
Headset to assist with focus and concentration. **how?** EEG

Memory: ***HUMM***
Expanding your working memory. **how?** tACS to your prefrontal cortex to simulate theta waves

Sleep: ***Dreem***
Providing sleep reports. **how?** EEG

Meditation: ***Muse***
Technology assisted meditation. **how?** EEG

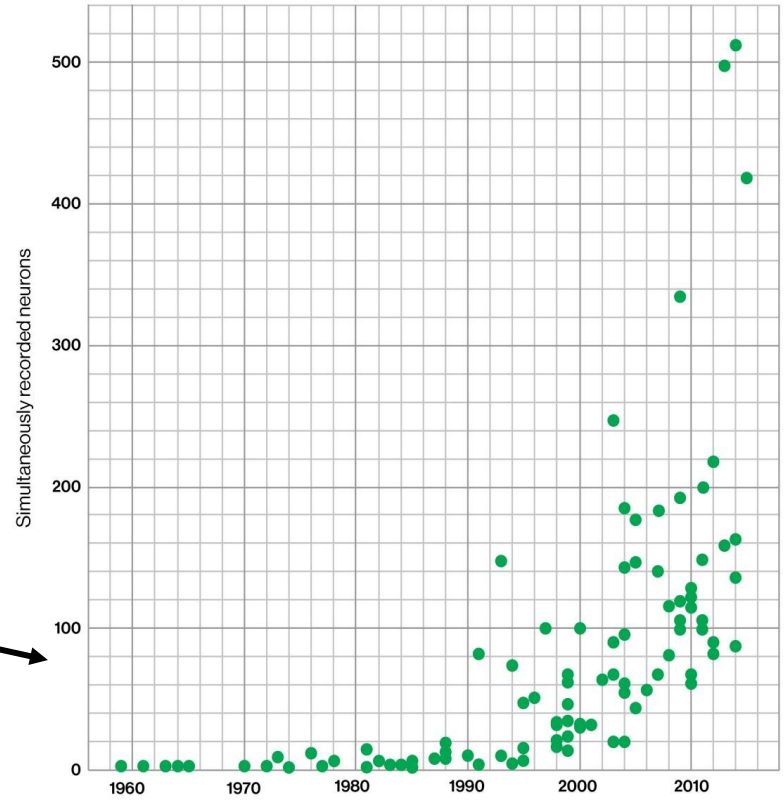


Let’s talk about the challenges

BANDWIDTH
HOW MANY NEURONS CAN WE RECORD SIMULTANEOUSLY?

- more neurons we can listen to → discern more of our motor intentions, thoughts, and vision
- **potentially useful #:** 100,000 neurons
- **world changing?** 1,000,000 neurons
- if we follow Moore’s law for transistors (transistor count on chip doubles every 18 months), we’ll reach million neurons by 2034
- **Stevenson’s Law:** double every 7.4 years, need till 2100 to reach 1,000,000

The Moore’s Law of Brain-Computer Interfaces
The number of neurons recorded simultaneously from any animal’s brain. Each point represents a published paper.



Source: Ian H. Stevenson, UConn

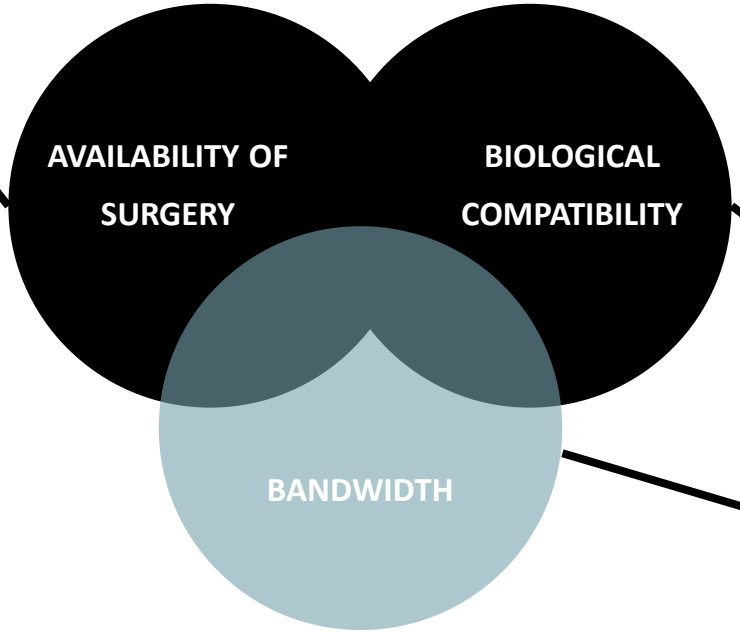
MIT Technology Review

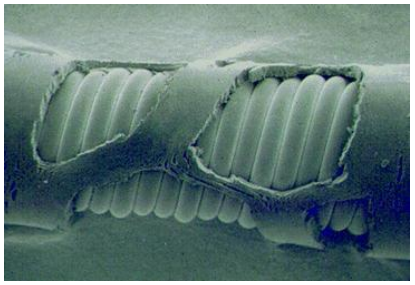
Let’s talk about the challenges (cont.)

IMPLANTATION

TO INVADE OR NOT TO INVADE

EXPENSIVE AND LIMITED





OUR BRAINS DON’T LIKE ELECTRONICS

CLOSER TO THE BRAIN, HIGHER BANDWIDTH!

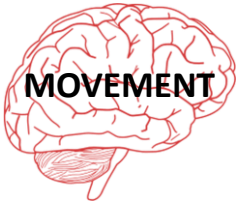
Elon Musk on Neuralink:

“The machine to accomplish this would need to be something like Lasik, an automated process—because otherwise you just get constrained by the limited number of neural surgeons, and the costs are very high. You’d need a Lasik-like machine ultimately to be able to do this at scale.”

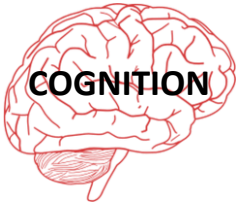
Let’s talk about the challenges (cont.)

SOME UNSOLVED NEUROSCIENCE PROBLEMS

What are the **causes of neurological disorders** such as Parkinson’s and Alzheimer’s?



How are our movements so **fine and controlled** if our motor nerve impulses are so **noisy and unpredictable**?



What is the neural basis of **decision making**?

Let’s talk about the challenges (cont.)

PUBLIC SKEPTICISM & ETHICS

Type with your mind: We've achieved a first in brain-computer research, says Facebook

Facebook makes progress on its ambitions to create a wearable to decode speech directly from your brain.

(July 2019)

Would you use this?

Facebook is ditching plans to make an interface that reads the brain

The company's research into a consumer mind-reading device is over, for now. Some scientists said it was never possible anyway.

By Antonio Regalado July 14, 2021