Can Neuromodulation Make Us Better: Changing Brain Activity with Wearable Brain Stimulation Devices

Marom Bikson
The City College of New York

Lucas Parra, Jacek Dmochowski, John Tarbell, Bingmei Fu, Greg Kronberg, Abhishek Datta, Dennis Truong, Niranjan Khadka, Davide Reato, Dennis Truong, Louis Zannou, Zeinab Esmaeilpour, Nigel Gebodh, Gozde Unal, Mohamad Rad, Limary Cancel, Andy Huang, Asif Rahman, Jaiti Swami, Carliza Canela, Samantha Cohen, Preet Minhas, Davide Reato, Cynthia Poon, Min-Fang Kuo, Michael A Nitsche, Mersedeh Bahr-Hosseini, Hanoch Kaphzan, Belen Lafon
Disclosure
The City University of New York holds patents on brain stimulation with MB as inventor. MB has equity in Soterix Medical Inc. MB consults, received grants, assigned inventions, and/or serves on the SAB of Boston Scientific, GlaxoSmithKline, Biovisics, Mecta, Lumenis, Halo Neuroscience, Google-X, i-Lumen, Humm, Allergan (Abbvie).

Support
NYS DOH, NIH (NIMH, NINDS, NIBIB), Grove Foundation, Harold Shames, CCNY Fund, 21st Century Fund
Neuromodulation technologies platforms vary in how energy is delivered to what target:

- **Implants**
  - Deep Brain Stimulation (DBS)
  - Spinal Cord Stimulation (SCS)

- **In-Hospital**
  - Transcranial Magnetic Stimulation (TMS)
  - Electroconvulsive Therapy

- **Wearable**
  - Transcranial Electrical Stimulation (tES)
  - Transcranial Direct Current Stimulation (tDCS)
Neuromodulation technologies platforms vary in how energy is delivered to what target.

- Deep Brain Stimulation (DBS)
- Transcranial Magnetic Stimulation (TMS)
- Transcranial Electrical Stimulation (tES)
- Spinal Cord Stimulation (SCS)
- Electroconvulsive Therapy
- Transcranial Direct Current Stimulation (tDCS)

Implants
In-Hospital
Wearable
Neuromodulation technologies platforms vary in how energy is delivered to what target:

- Spinal Cord Stimulation (SCS)
- Transcranial Magnetic Stimulation (TMS)
- Deep Brain Stimulation (DBS)
- Electroconvulsive Therapy
- Implants
- In-Hospital
- Transcranial Direct Current Stimulation (tDCS)
- Transcranial Electrical Stimulation (tES)

Neuromodulation in every-day life: “In the wild.”
Neuromodulation “in the wild.”

Credit: Halo Neuroscience

Credit: mBrainTrain / Soterix Medical

Credit: Y-Brain
How does it work? It depends.

1. Energy is directed to targeted regions of the nervous system (e.g., motor cortex).
2. Neuronal activity of modulated (e.g., increased function / plasticity).
3. Changing cognition or behavior (e.g., reaction time).

• Targeting depends on type of energy (delivery technology).
• Neuromodulation depends on type of energy.
• Depends on underlying brain state / activity
How does it work? It depends.

1. Energy is directed to targeted regions of the nervous system (eg. motor cortex).
2. Neuronal activity of modulated (eg. increased function / plasticity).
3. Changing cognition or behavior (eg. reaction time).

- Targeting depends on type of energy (delivery technology).
- Neuromodulation depends on type of energy.
- Depends on underlying brain state / activity.
Conventional (Pad) tDCS

Brain Activation
- Maximum
- Moderate
- Minimum

(Electric Field)

Datta et al. Gyri-precise model of tDCS/ Brain Stimulation 2009
Conventional (Pad) tDCS

With pad electrodes: Current reaches brain, is electrode position specific, but modulates networks.

Datta et al. Gyri-precise model of tDCS/ Brain Stimulation 2009
High-Definition tDCS – 4x1

Brain Activation
Maximum
Moderate
Minimum
(Electric Field)

Datta et al. Gyri-precise model of tDCS/ Brain Stimulation 2009
High-Definition tDQS – 4x1

With HD electrodes: Current can be directed to targeted brain regions.

With battery-powered wearable technology

Datta et al. Gyri-precise model of tDQS/ Brain Stimulation 2009
High-Definition tDCS: Non-invasive targeted brain stimulation with wearable technology

1. Develop the hardware (HD electrode).

2. Show lasting functional neuromodulation.
   Kuo et al. Comparing cortical plasticity induced by conventional and high-definition 4 × 1 ring tDCS. Brain Stim 2013

3. Closed-form optimization to any target.
   Dmochowski et al. Optimized multi-electrode stimulation increases focality and intensity at target. J Neural Engr 2011

4. Intra-cranial recording to validate models.
   Huang et al. Measurements and models of electric fields in the in vivo human brain during transcranial electric stimulation. Elife 2017

5. Behavior and cognition changes. (200x, too many indications?)
How does it work? It depends.

1. Energy is directed to targeted regions of the nervous system (eg. motor cortex).
2. Neuronal activity of modulated (eg. increased function / plasticity).
3. Changing cognition or behavior (eg. reaction time).

- Targeting depends on type of energy (delivery technology).
- Neuromodulation depends on type of energy.
- Depends on underlying brain state / activity.
Direct Current Stimulation polarizes neurons (especially synaptic terminals), modulates I/O, and boosts Hebbian plasticity. (or it does something else…)
Neurovascular modulation

- Neurons are not alone in the brain.
- Neuronal stimulation must consider neurovascular coupling.
- Direct stimulation of brain vasculature
• Electric fields are concentrated across the Blood-Brain-Barrier (>400x in brain parenchyma).


• Isolated Blood-Brain-Barrier models (no neurons) respond to stimulation

  Cancel et al. Direct current stimulation of endothelial monolayers induces a transient and reversible increase in transport due to the electroosmotic effect. Scientific Reports 2018
Direct Current Stimulation polarizes neurons (especially synaptic terminals), modulates I/O, and boosts Hebbian plasticity. (or it does something else…)

Chakraborty et al. Neuromodulation of Axon Terminals. *Cerebral cortex* 2018
Lafon et al. Direct current stimulation alters neuronal Input/Output function. *Brain Stim* 2017
How does it work? It depends.

1. Energy is directed to targeted regions of the nervous system (e.g. motor cortex).
2. Neuronal activity of modulated (e.g. increased function / plasticity).
3. Changing cognition or behavior (e.g. reaction time).

- Targeting depends on type of energy (delivery technology).
- Neuromodulation depends on type of energy.
- Depends on underlying brain state / activity
Closed-loop stimulation: Measuring brain activity to optimize neuromodulation.

(an old new idea)
Closed-loop stimulation: Measuring brain activity to optimize neuromodulation.

(an old new idea)

- All data and code open-source, 19 subjects
- >72 hours Compensatory Tracking Task (CTT)
- Continuous EEG (32 chan), ECG, EOG
- 9 types of open-loop High-Definition Transcranial Electrical Stimulation
- Train closed-loop algorithm


github.com/ngebodh/GX_tES_EEG_Physio_Behavior
Can Neuromodulation Make Us Better: Changing Brain Activity with Wearable Brain Stimulation Devices

Marom Bikson
The City College of New York

Lucas Parra, Jacek Dmochowski, John Tarbell, Bingmei Fu, Greg Kronberg, Abhishek Datta, Dennis Truong, Niranjan Khadka, Davide Reato, Dennis Truong, Louis Zannou, Zeinab Esmaeilpour, Nigel Gebodh, Gozde Unal, Mohamad Rad, Limary Cancel, Andy Huang, Asif Rahman, Jaiti Swami, Carliza Canela, Samantha Cohen, Preet Minhas, Davide Reato, Cynthia Poon, Min-Fang Kuo, Michael A Nitsche, Mersedeh Bahr-Hosseini, Hanoch Kaphzan, Belen Lafon

Slides and References @MaromBikson