Transcranial Alternating Current Stimulation - tACS

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A growing field

“tACS allows to modulate brain oscillations in a frequency specific manner”

**TMS**: Transcranial Magnetic Stimulation

**tDCS**: transcranial Direct Current Stimulation

**tACS**: transcranial Alternate Current Stimulation

**tRNS**: transcranial Random Noise Stimulation

Santarnecchi et al. 2015 Curr Opin Behav Sci
Outline

• Oscillatory pattern and synchronicity in the brain
  ✓ tACS - Mechanism of action

• tACS evidence
  ✓ Perception (Hands-On session tomorrow)
  ✓ Cortico-spinal excitability and motor system
  ✓ Cognition
  ✓ Phase-Related activity
  ✓ State and Trait – dependency
  ✓ Therapeutic potential

• Future Directions

- Kirsten Building - KS-450
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Emiliano Santarnecchi serves as consultant for EBN euro, a joint stock company developing biomedical devices for neurostimulation, neuromodulation and electroencephalography.

He has no actual or potential conflict of interest in relation to this presentation, none of the tools presented in the following slides are property of EBN euro.
• Experience with EEG/Brain Oscillations?

• Experience with tACS?
### TCS Techniques

**A**

<table>
<thead>
<tr>
<th><strong>Transcranial Direct Current Stimulation (tDCS)</strong></th>
<th><strong>Transcranial Random Noise Stimulation (tRNS)</strong></th>
<th><strong>Transcranial Alternating Current Stimulation (tACS)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Parameters: Constant/Direct</td>
<td>Oscillatory/Alternating</td>
<td>Oscillatory/Alternating</td>
</tr>
<tr>
<td>Stimulation Mechanism: Membrane polarization</td>
<td>1-640 Hz (random)</td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>Anode: excitatory</td>
<td>100-640 Hz: excitatory</td>
<td>Phase (Degrees)</td>
</tr>
<tr>
<td>Cathode: inhibitory</td>
<td>Stochastic resonance</td>
<td>Entrainment</td>
</tr>
<tr>
<td>Effect on Neuronal Excitability: Cortical excitability</td>
<td>Cortical excitability</td>
<td>Brain oscillations (power, phase)</td>
</tr>
<tr>
<td>Neuronal Effect: During and After</td>
<td>During and After</td>
<td>Cortical excitability (&gt;100Hz)</td>
</tr>
</tbody>
</table>

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Santarnecchi et al. 2015 Curr Opin Behav Sci
Brain Oscillatory Activity

Hans Berger

**EEG Signal**
- Frequency ~ 10 Hz
- Instantaneous Phase ~ π/2
- Instantaneous Amplitude ~ 24 μV

**Frequency**
- Delta
- Theta
- Alpha
- Beta
- Gamma

**10 log(μV²/Hz)**

**Time**
0.5 Sec
**“Natural Frequencies”**

**Alpha**: automatic movements

**Beta**: movement

**Gamma**: selective attention

**Theta**: working / long-term memory

**Alpha**: visual perception

**Theta**: spatial orienting
Oscillatory pattern and periodicity in behaviour

Cyclic patterns in behaviour

**Sleep–wake cycles** are evident even if external light conditions are held constant (grey shade)

**Intrinsic oscillators** (circadian clocks) which cause periodicity in bodily function

**Frequency?**
Number of cycles x second (1 cycle * second=1Hz)

Phase?
Phase, angles, degrees.....

Oscillators are in opposite phase (anti-phase)
"Entrainment" phenomenon

- Are these oscillatory patterns immutable?

**Entrainment** of endogenous oscillatory pattern $\rightarrow$ Changes in behaviour

- Oscillatory cycle establishes a recurrent temporal reference frame that allows for the coding of temporal relations between groups of neural elements.
- This reference frame is not fixed but is subject to dynamic changes (phase resetting), especially in pathological states.

**tACS induces entrainment of brain oscillations following the same principle** (theta, alpha, beta, gamma, ..)

*Tuth et al.* 2012, *Current Biology*
Mechanism of action

DC Stimulation

Constant Fields

Membrane Polarization

Spike Rate Change

AC Stimulation

Oscillating Fields

Network Synchrony

Spike Phase Change

Synchrony Effect

Synchronize the Input

Amplify the Output

Direct Current

Alternating Current
tACS effect

Pre stimulation spectral power and average phase

B(t)
Why tACS? (2)
**EEG Oscillations and BEHAVIOURAL CORRELATES**

- **Delta (1 – 4 Hz)**
  - Sleep, learning, motivational processing

- **Theta (4 – 8 Hz)**
  - Memory, emotional regulation, creativity

- **Alpha (8 – 13 Hz)**
  - Active inhibition of task-irrelevant areas

- **Beta (13 – 30 Hz)**
  - Mainly Motor activity

- **Gamma (30 – 80 Hz)**
  - Abstract mental activity, cognitive control, perceptual binding
**EEG Oscillations and PATHOLOGY**

- **Delta (1 – 4 Hz)**
  - Reduced synchrony in Schizophrenia
  - Reduced amplitude in Alzheimer
  - Increased Amplitude in Bipolar dis.

- **Theta (4 – 8 Hz)**
  - Reduced synchrony in Schizophrenia
  - Reduced synchrony in Alzheimer

- **Alpha (8 – 13 Hz)**
  - Reduced coherence in Alzheimer
  - Increased phase-locking at Frontal and Central electrodes in Schizophrenia

- **Beta (13 – 30 Hz)**
  - Reduced Coherence in Alzheimer and Schizophrenia
  - Increased amplitude in Parkinson
  - Increased Coherence in Bipolar dis.

- **Gamma (30 – 80 Hz)**
  - Decreased/increased amplitude in Schizophrenia (?)
  - Increased Phase-locked response in ADHD
Frequency-specific effects?

**Alpha**: automatic movements

**Theta**: working/long-term memory

**Beta**: movement

**Gamma**: selective attention

**Alpha**: visual perception

**Theta**: spatial orienting
tACS: experimental evidence
tACS effect on brain oscillations: in vitro evidence

Endogenous Electric Fields May Guide Neocortical Network Activity

Flavio Fröhlich and David A. McCormick

1Department of Neurobiology, Kavli Institute of Neuroscience, Yale University School of Medicine, 333 Cedar Street, New Haven, CT 06510, USA
2Correspondence: david.mccormick@yale.edu
DOI 10.1016/j.neuron.2010.06.005

Higher stimulation frequency

tACS might shift intrinsic dominant oscillations and “tune the system”
First animal evidence

- tACS induce AC Fields in the Brain

- Effect of Stimulation Amplitude

Larger Amplitude → Homogenous Phase More Neurons

Ozen et al., 2010
Endogenous Resonance Principle

**tACS induced Oscillations** ↔ **Synaptic mediated Oscillations**

**Coherent** ↔ **Incoherent**

**Sleep** → **tACS ~1.5Hz** → **Exploring**

- **S**=sleep
- **R**=rest
- **E**=exploration

**Phase-locked** (25-50%)

**No Phase-locked**

*Ozen et al., 2010*
tACS and Cortico-spinal Excitability
**tACS and Corticospinal Excitability**

**Question**
- Are beta oscillations in motor cortex functional or epiphenomenon?

**Design**

<table>
<thead>
<tr>
<th>tACS</th>
<th>10xTMS</th>
<th>10xTMS</th>
<th>10xTMS</th>
<th>10xTMS</th>
<th>10xTMS</th>
<th>10xTMS</th>
<th>10xTMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrodes</td>
<td>C4 (TMS hot-spot) + P4 (control) − Pz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>5, 10, 20, 40Hz, 0.5mA*, 90s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subjects</td>
<td>15 Healthy</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

* Kept below phosphenoe or skin sensation threshold.

* MEP- Motor Evoked Potential, indicating the strength of the corticospinal response
Motor Evoked Potentials (MEPS)

Transcranial Magnetic Stimulation + Electromyography

Descending Volleys

Motor Evoked Potentials

Peak-to-Peak Amplitude

Latency

Magnetic Field

PLEASE DO NOT COPY
Results

• Parietal tACS @ 20HZ specifically increases MEP amplitude
tACS and Motor performance
tACS and Motor performance

**Question**

- Are Gamma oscillations in motor cortex functional or epiphenomenon?

*Santaruncchi et al., under revision*

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**Muthukumaraswamy 2010**

- Tracking task using MEG
- Observed an Increase in Gamma activity (~90HZ) in the motor cortex during movement.

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- What does Gamma oscillations in the motor cortex represent?..?
Question

- Are Gamma oscillations in motor cortex functional or epiphenomenon?

**Visuomotor task + 10, 20, 60, 80Hz and Sham tACS** on the motor cortex.

Effects on several components of the motor program: Acceleration, Pursuit, Loops, Turns, etc.

High spatial and temporal resolution analyses.
tACS and Motor performance - II

A

TURNs (200–700ms)

Displacement

β θ γ 1 γ 2

60Hz 80Hz

Sham

p < 0.1

B

TURNs (0-200ms)

TURNs (500–2000ms)

Displacement

θ β γ 1 γ 2 Sham

C

LOOP ACCELERATION PURSUIT

Displacement

θ β γ 1 γ 2 Sham

Displacement

θ β γ 1 γ 2 Sham

Displacement

θ β γ 1 γ 2 Sham

Significant enhancement of performance during TURNs during Gamma tACS (80Hz), with a trending result for 60Hz tACS.

Effect is present in a specific time window (200-700ms after each TURN), coherently with MEG studies showing increase in EEG power at 90HZ during a similar task.

No effects during Loop, Acceleration, Pursuit

PLEASE DO NOT COPY
tACS and Motor performance

**Question**

- Are beta oscillations in motor cortex functional or epiphenomenon?

| Visuomotor Task + 20Hz tACS/Sham | Reaction time + EEG-EMG |

**Design**

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>C4 (TMS hot-spot) – P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>20Hz, 0.6mA*, -2s to +8s</td>
</tr>
<tr>
<td>Subjects</td>
<td>14 Healthy</td>
</tr>
</tbody>
</table>

* Kept below phosphene or skin sensation threshold.
Results

- Parietal 20Hz tACS slowed initial velocity (small effect)
- Parietal 20Hz tACS increased somatosensory-arm 20Hz coherence

Pogosyan et al., 2009
tACS and Cognition
Memory Consolidation

**Rationale**

**Sleep Architecture**

- **Wake**
- **REM**
- **Stage 1**
- **Stage 2**
- **Stage 3**
- **Stage 4**

- **Early sleep**
- **Late sleep**

**Slow oscillation** (neocortex) - 0.8Hz

**Spindle** (thalamus) - 8-14Hz

**Sharp wave-ripple** (hippocampus) - 100-300Hz

**Non-Declarative memory**

**Declarative memory**

- **PGO wave** (Pons-LGN)
- **Theta activity** (hippocampus) - 4-8Hz

*PGO: ponto-geniculooccipital*

For further reading see Diekelmann, 2010
Memory Consolidation

Design

**Declarative memory**

**Paired Associated Learning Task**
- 46 word pairs

**Finger Sequence Tapping Task**
- 5-element sequences (e.g., 4-2-3-1-4) in 30s

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**Non-declarative memory**


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**Learning**
- 9p
- 10:30p
- 11p

**Recall**
- 6:30a
- 7a
- 8:30a

W, wake; 1–4, sleep stages 1–4

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**Electrodes**
- F3-Mastoid, F4-Mastoid (diam=1cm)

**Current**
- 0.75Hz, ~0.33A, 5min/1min ON/OFF

**Subjects**
- 13 Healthy
Results

- Bilateral 0.75Hz frontal- tACS during early sleep selectively enhances hippocampus-dependent retention of declarative memory

**P < 0.01
Results

- tACS entrained SWS and spindle power spectra in the prefrontal region

* Bands for slow oscillations (0.5–1 Hz); Bands for spindle oscillations (8-12 Hz)
tACS effects on Risk Taking

Rationale

• Right > Left Theta oscillations PFC

(Gianotti, 2009)

But... **bilateral DLPFC tDCS** (regardless of polarity) facilitate risk-adverse behaviour in Balloon Analog Risk Task (BART) (Fecteau, 2007)

PFC: prefrontal cortex
**tACS effects on Risk Taking**

**Question**
Does theta oscillation in PFC affect risky decision making?

- theta tACS PFC Left/Right/Sham
- pumps in Balloon Analog Risk Task

**Design**

**Balloon Analog Risk Task (BART)**

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>F3-CP5, F4-CP6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>6.5Hz, 0.5mA, -5min +10mins</td>
</tr>
<tr>
<td>Subjects</td>
<td>27 Healthy</td>
</tr>
</tbody>
</table>
Results

- Theta tACS over left and not right PFC increases risk taking behavior

Sela et al., 2012

Error bars indicate SEM. *p < 0.05.
Fluid Intelligence – Abstract Reasoning

**Question**

- Does tACS enhance Intelligence-related processing in a frequency and trial specific manner? Is prefrontal gamma an epiphenomenon?

**Design**

- tACS condition: randomized, balanced order
  - 5 Hz (0)
  - 10 Hz (α)
  - 20 Hz (β)
  - 40 Hz (γ)
  - SHAM

- 12 trials x 4 trial types (fully randomized order)
- Resting period (20’)
- Control task (odd-even)

- Stimulation sites

- N=24; tACS 1.250mA
- Logical and Relational Reasoning Stimuli

*Santarnechi et al., Curr. Biology 2013*
Results

- Decrease of Correct trials Response Time during gamma-tACS
- Selective effect for Logic trials.
- First evidence of a “causal” Role of gamma-oscillations in higher-order cognition.

Santar necchi et al., Curr. Bio 2013

No modulation of speed-accuracy tradeoff
Design and Results

- Torrance Test of Creative Thinking (TTCT)
- In-phase tACS over the prefrontal lobes
- Sham, 10Hz and 40Hz tACS

Lustenberger et al., Cortex 2015

10Hz tACS effect on a Creativity Index

Improvement by 10Hz-tACS [%]

- Fluency
- Originality
- Elaboration
- Abstraction of Tities
- Resistance to Premature Closures
Phase-Related Modulation by tACS
The Importance of Timing in Segregated Theta Phase-Coupling for Cognitive Performance

**Question**
- Can we modulate synchronization during working memory processing? Does it matter?

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**Sternberg Working memory task**

**Band-pass 6 +/- 1 Hz**
Design and Results

Polania et al., Curr. Bio 2012

WM performance
State Dependency of tACS
State Dependency: Motor Imagery

State-Dependent Effects of Transcranial Oscillatory Currents on the Motor System: What You Think Matters

Question
• Does the effects of tACS depend on brain state?

N=18, tACS= 1mA (peak-to-peak).
State Dependency

Results

Consistent increase of MEP size during Motor Imagery versus the quiescence state, regardless of the type of tACS applied.

Dissociation between tACS (5 Hz) and tACS (20 Hz), after removing the average facilitatory main effect of motor imagery.
State Dependency

Orchestrating neuronal networks: sustained after-effects of transcranial alternating current stimulation depend upon brain states

- Does the after-effects of tACS depend on the endogenous power of oscillations?

Exp. 1: 19 sbjs, 20’ tACS at Individual Alpha frequency*, Eyes Open

Exp. 2: 29 sbjs 20’ tACS at Individual Alpha frequency*, Eyes Closed

*power peak in the alpha range (8–12Hz)
tACS effect depend on brain states During the stimulation...

- Alpha reaches a plateau during Eyes Closed condition
Trait-dependency of tACS?
Individual differences in response to tACS?

Santornecchi et al., 2016

**A**
Fluid Intelligence (Gf)
- Relational
- Logic

Working Memory (WM)
- Fixation (2000ms)
- Sample (100ms)
- Delay (800ms)
- Probe

Change Localization task

Response time for Logic

Experiment 1
- Sham
- 0
- γ
- p<0.001, p<0.01

**B**
- γ-tACS
- SHAM
- Counterbalanced task order
- Rest period (30s)
- Control task (odd-even, 100 trials)
- Randomized Gf trials (REL, LOGIC)

STUDY 1: φ-tACS (5Hz, n=24)
STUDY 2: tRNS (θ-64Hz, n=24)

Response time for Logic

Experiment 2
- Sham
- tRNS
- γ
- p<0.05, p<0.05

N=58
tACS=1.0 mA,
tRNS=1.0 mA

Confirmed previous finding
**Individual differences in response to tACS?**

*Santarnecchi et al., 2016*

- Effect of tACS reflect individual differences, which can be considered a stable “Phenotype”

- Relevant for the ethical evaluation of cognitive enhancement intervention

\[ \text{tACS} = 1.0 \, \text{mA}, \, \text{tRNS} = 1.0 \, \text{mA} \]
Therapeutic Potential of tACS
tACS in Stroke...

Ninety-eight patients that had suffered ischemic stroke 21.4 months earlier were randomly assigned to either:

1) **group D** (n = 30) receiving conventional drug therapy
2) **group ACS** (n = 32) treated for 12 days with tACS (~20Hz, 30’)
3) **group D/ACS** (n = 36) receiving combined drug therapy/tACS.

*Stroke severity level (SSL)* was assessed by the NIH-NINDS stroke scale before and after treatment and at a 1-month follow-up to evaluate motor impairments (weakness, ataxia), sensory loss, visual field defects, and cortical deficits (aphasia, neglect).

At each time point standard **EEG recordings** (10–20 system) were conducted.
Table 3
Results of SSL assessment (NIH-NINDS stroke scale) for ischemic post-stroke patients before, after 12 days and 1 month follow-up

<table>
<thead>
<tr>
<th>NIH-NINDS scale</th>
<th>Group D, n = 30</th>
<th>Group ACS, n = 32</th>
<th>Group D/ACS, n=36</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>Facial palsy</td>
<td>1.56</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Motor arm right</td>
<td>0.75</td>
<td>0.70</td>
<td>1.17</td>
</tr>
<tr>
<td>Motor arm left</td>
<td>0.44</td>
<td>0.44</td>
<td>0.17</td>
</tr>
<tr>
<td>Motor leg right</td>
<td>0.63</td>
<td>0.57</td>
<td>1.25</td>
</tr>
<tr>
<td>Motor leg left</td>
<td>0.50</td>
<td>0.50</td>
<td>0.17</td>
</tr>
<tr>
<td>Limb ataxia</td>
<td>1.38</td>
<td>1.38</td>
<td>1.50</td>
</tr>
<tr>
<td>Sensory</td>
<td>1.13</td>
<td>1.13</td>
<td>1.08</td>
</tr>
<tr>
<td>Formerly neglect</td>
<td>1.13</td>
<td>1.13</td>
<td>1.08</td>
</tr>
<tr>
<td>Dysarthria</td>
<td>0.50</td>
<td>0.45</td>
<td>0.58</td>
</tr>
<tr>
<td>Aphasia</td>
<td>0.25</td>
<td>0.20</td>
<td>0.42</td>
</tr>
<tr>
<td>SSL</td>
<td>8.27</td>
<td>8.0</td>
<td>8.92</td>
</tr>
</tbody>
</table>

SSL: Stroke severity level. Significant differences between post minus pre or follow-up minus pre measurements are marked with * (p < 0.05).

Aphasia subscale
Rationale

- Can tACS reduce tremor in PD patients?

Design

**Closed-loop** tACS – tremor phase (accelerometer)

Tremor amplitude (accelerometer)
Tremor Suppression?

Identification of the optimal Phase-Delay for tremor suppression

Phased-locked tACS reduced tremor by up to 50%

Brittain et al., Curr. Bio 2013

Tremor Excitation

Tremor Suppression
**Question**

- Can tACS restore lost vision in optic neuropathy?

**Design**

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>Transorbital (above-below eye)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td><em>Individual alpha- flicker frequency</em>, phosphene threshold (&lt;1mA), <strong>15min x 10 days</strong></td>
</tr>
<tr>
<td>Subjects</td>
<td>24 patients with visual field loss caused by damage to the optic nerve</td>
</tr>
</tbody>
</table>

*Sabel et al., 2011 (RCT)*
Visual Restitution Training (VRT)

Kasten, 1998

- Software designed for patients with visual field defects caused by optic nerve diseases and post-chiasmal brain lesions.

- Binocular visual stimulation within a transition zone between the intact visual field area and the field defect.
Results

**High Resolution Perimetry Visual Field**

1. Intact  
2. Relative defect  
3. Absolute defect

![Graph showing mean DA change over time](image)

- **Baseline**
- **Post rtACS**
- **Follow-up**

**Improved:**
- temporal processing of visual stimuli
- detection performance in static perimetry
- visual acuity

Blue = increase, Red = decrease DA

*Sabel et al., 2011 (RCT)*
**Results**

- tACS restored some lost vision in patients with optic neuropathy.
- The effect was accompanied by an increase in occipital alpha spectrum.

*Sabel et al., 2011 (RCT)*
Rational

- Patients with tinnitus have **lower alpha activity at the right PFC**.

Mean Alpha Spectrum

Red: high distress > low distress  Blue: high distress < low distress

- **tDCS** (left temporal or bifrontal) reduce tinnitus intensity (e.g. Song 2012)

Measured with EEG and Low Resolution Electromagnetic Tomography (LORETA)
Results

Vanneste et al., 2013 (RCT)

Tinnitus Intensity Rating

• **left-right DLPFC tACS** in the alpha “band” was **not effective as tDCS** in reducing tinnitus intensity (and annoyance).
Random level of current generated for every sample. The signal is normally distributed, with the current intensity constantly fluctuating around 0uA. For a 1mA amplitude, 99% of the Current is between -500/500uA (Peak to Peak amplitude).

Stimulation frequency constantly change within a predefined spectrum.

Terney et al., 2008 (first tRNS evidence)
tRNS – Neurophysiological evidence

Experiment 1
10’
tRNS (1-640Hz)

Experiment 2
10’
tRNS (1-100Hz) vs (101-640Hz)

Stimulation site: Primary Motor Cortex, Premotor cortex

Electrophysiological evaluation: Motor Evoked Potential (MEP), Recruitment Curve, Short-Interval Intracortical Inhibition (SICI), Intracortical Facilitation (ICF), Long-Interval Intracortical Facilitation (LICI), Cortical Silent Period (CSP).

Behavioural evaluation: Serial Reaction Time Task (SRTT)
**tRNS - Results**

**Experiment 1**

**tRNS (1-640Hz)**

Increase in cortical excitability lasting for 60' after stimulation.

**tRNS improves implicit motor learning** in its early phase (<RT).

**Experiment 2**

**tRNS (1-100Hz) vs (101-640Hz)**

Effect is selective for **High-Frequency tRNS** (101-640Hz)

**Significant effect on ICF (12, 15ms)**

No changes in Recruitment Curve, SICI, LICI, CSP.

No effect for premotor cortex stimulation.
• tRNS on **Bilateral Dorsolateral Prefrontal Cortex** (DLPFC), a key region in **Arithmetic**.

• **5 Days of training** (Calculation and Memory-recall-based arithmetic training) + tRNS/Sham

• Near Infrared Spectroscopy (NIRS) recording during training

**Calculation learning rates increase during tRNS**

**tRNS effect correlates with changes in the hemodynamic response**
tES Methods

**Transcranial Direct Current Stimulation (tDCS)**
- Current: Constant/Direct
- Stimulation parameters: Anode: excitatory, Cathode: inhibitory
- Mechanism: Membrane polarization
- Effect on: Cortical excitability
- Neuronal effect: During and After

**Transcranial Random Noise Stimulation (tRNS)**
- Oscillatory/Alternating
- Stimulation parameters: 1-640 Hz (random), 100-640 Hz: excitatory
- Mechanism: Stochastic resonance
- Effect on: Cortical excitability
- Neuronal effect: During and after

**Transcranial Alternating Current Stimulation (tACS)**
- Oscillatory/Alternating
- Stimulation parameters: Frequency (Hz), Phase (Degrees), Entrainment
- Effect on: - Brain oscillations (power, phase), - Cortical excitability (>100Hz)
- Neuronal effect: During and After
Summary

Principles of tACS

- Oscillations
- Endogenous Resonance

**tACS probe oscillatory neural activities**

- Perception (vision, tactile) (HANDS-ON session)
- Cortico-Spinal Excitability
- Cognition (Intelligence, memory, risk-taking,...)

Potential therapeutic tool

- Visual restoration, tremor, stroke..

**Future Directions?**
Grazie dell’attenzione

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