Cognitive Enhancement with Transcranial Direct Current Stimulation (tDCS)

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Neuroenhancement

The enhancement of brain processes in healthy individuals
Cognitive Enhancement with tDCS
(Coffman et al., 2014; Horvath et al., 2015)

- Executive functions
  - Set-shifting
  - Stop signal tasks
  - Stroop tasks
- Language
  - Grammatical learning
  - Lexical learning
  - Verbal fluency
  - Naming
- Attention
  - Selective attention
  - Spatial attention
- Learning
  - Motor learning
  - Procedural learning
  - Explicit learning
  - Numerical learning
- Memory
  - Digit-span recall
  - Verbal episodic memory
  - Visual working memory
  - N-back working memory
- Mental arithmetic
- Automaticity
- Picture viewing/rating
- Visual perception
- Multimodal perception
- Social cognition
- Problem-solving
- Mood
- Gambling based risk taking
- Rumination

Santarnecchi et al., in prep
Cognitive Skills

• Learning
  – Implicit
    • Motor/procedural
    • Probabilistic
  – Explicit
• Working Memory
• Attention
• Social Cognition
• Language
• Complex Problem-Solving
Enhancement of Implicit Learning: Procedural/Motor

• Anodal tDCS of the left primary motor cortex enhances motor learning of the contralateral hand (Nitsche et al., 2003)

• Cathodal tDCS of the primary motor cortex decreases motor learning of the contralateral hand (Vines et al., 2006)

• Cathodal tDCS enhances motor learning of the ipsilaterial hand
Enhancement of Implicit Learning: Procedural/Motor

• Learning occurs in 3 stages
  – Acquisition ➔ Consolidation ➔ Retention
• tDCS improves motor learning by enhancing consolidation (Reis et al., 2009)

• Others have shown additional improvements in retention (Galea & Celnik, 2009)
Enhancement of Implicit Learning: Probabilistic

- Probabilistic Classification Learning Task (Kincses et al., 2004)
Enhancement of Implicit Learning: Probabilistic

- Anodal tDCS of the left dorsolateral prefrontal cortex (DLPFC) enhances probabilistic learning (Kincses et al., 2004)
Enhancement of **Explicit Learning**

- Enhancement of explicit learning consolidation during sleep (Marshall et al., 2004)
  - List of words presented to subjects during the day
  - Anodal tDCS of bilateral DLPFC during slow wave sleep
  - Enhanced recall of word list

- Anodal tDCS of right temporoparietal area enhances memory of object locations after a 1 week delay (Flöel et al., 2011)
  - However, no difference in immediate acquisition
Physiology of Learning Enhancement

- Clark et al. found improvement in spatial learning with anodal tDCS to right parietal cortex (2012)
- They then use magnetic resonance spectroscopy to measure metabolites under anode (2011)
- Elevations in:
  - Glutamine/glutamate (Glx)
  - N-acetylaspartate/N-acetylaspartylglutamate (tNAA)
Physiology of Learning Enhancement

- **Glx**
  - Glutamate (Glu) is major excitatory neurotransmitter
  - Metabolized to glutamine (Gln)
  - Glutamate binds to NMDA receptor for excitation, long-term potentiation
  - NMDA antagonists suppress tDCS effects, while NMDA agonists enhance tDCS effects (Clark et al., 2011)

- **tNAA**
  - Thought to be related to neuronal energy status
  - May be due to increased metabolic activity from increased glutamatergic activity
Enhancement of Working Memory

- The N-back working memory task (Fregni et al., 2005)
Enhancement of Working Memory

- Anodal tDCS of left DLPFC enhances performance on 3-back working memory task (Fregni et al., 2005)

![Graph showing correct responses]

- Anodal tDCS of the left DLPFC, combined with N-back working memory task, enhances digit span (Andrews et al., 2011)
  - Neither tDCS nor N-back testing alone was sufficient
Physiology of Working Memory Enhancement

• Anodal (compared to cathodal) tDCS of the left DLPFC during a 2-back working memory task (Zaehle et al., 2011):
  – Enhanced working memory
  – Increased alpha and theta frequencies

• Alpha and theta frequencies have been linked to working memory (Klimesch et al., 2005)
  – Alpha thought to inhibit non-task relevant areas
  – Theta associated with memory encoding and retrieval
Enhancement of Attention

- Executive Attention: Sternberg task (Gladwin et al., 2012)
Enhancement of Attention

- Anodal tDCS of the left DLPFC improved reaction time on only on high-interference probes (Gladwin et al., 2012)
Enhancement of **Attention**

- Visual Attention Task: Air Traffic Control (Nelson et al., 2014)
Enhancement of Attention

- With sham tDCS, attention decreases over time (Nelson et al., 2014)
  - Lower target detection rate
  - Slower reaction times
  - Reduction in cerebral blood flow velocity

- Anodal tDCS of the DLPFC (left or right) enhances attention
  - Higher target detection rate
  - Maintained blood flow velocity
  - Increased cerebral oxygenation
Enhancement of Attention

• Spatially-Specific Attention Task (Sparing et al., 2009)
Enhancement of Attention

Enhancement of Attention

- Anodal tDCS of parietal cortex enhances visual detection in the contralateral visual field (Sparing et al., 2009)
Enhancement of Social Cognition

- Subjects quickly shown a series of happy, sad, or neutral faces
- Asked to identify either happy or sad faces
- Anodal tDCS of the left temporal cortex & cathodal tDCS of the right temporal cortex enhances recognition of sad faces
  - ... only in women
  - Impairs recognition of sad faces in men
Enhancement of Language

• Anodal tDCS of Broca’s area enhances grammatical learning (de Vries et al., 2009)

• Anodal tDCS of Wernicke’s area enhances lexical learning (Flöel et al., 2008)
Enhancement of Complex Cognition

• Remote associates test (Cerruti & Schlaug, 2009)
  – Given 3 words, have to find a word associated with all 3
  – E.g., “Child, Scan, Wash”
  – Answer: “Brain”

• Anodal tDCS of the left DLPFC enhances performance
Mood enhancement

• Observed that tDCS can induce mood changes in healthy subjects
• Marshall et al., (2004) found improvement in mood with anodal tDCS of bilateral DLPFC
• tDCS investigated as treatment for depression
• However, recent placebo-controlled studies have found no mood changes with tDCS, with various positions and polarity (Plazier et al., 2012)

http://www.thync.com/

http://icdn4.digitaltrends.com/image/thync_6214-1500x1000.jpg
Cognitive Enhancement with tDCS

Santarnecchi et al., *in prep*
Cognitive Enhancement with tDCS: Stimulation Sites

- Motor Learning
- Probabalistic Learning
- Explicit Learning
- Working Memory
- Attention
- Social Cognition
- Language
- Complex Cognition
Cognitive Enhancement with tDCS: Stimulation Sites

Stimulation Sites:

- P3 4%
- P4 4%
- P8 2%
- T3 2%
- Cerebellum 2%
- CP5 13%
- CP6 2%
- F1 6%
- F4 7%
- F5 6%
- F6 6%

Left DLPFC:

- F3 56%
- CP5 13%
- CP6 2%
- C3 2%
- P3 4%
- P4 4%
- P8 2%
- T3 2%

Left DLPFC:

- Cognitive control 3%
- Creativity 3%
- Implicit learning-memory 5%
- Attention 3%
- Problem solving 3%
- Language 16%
- WM 40%
- STM 16%
- LTM 11%

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Different Networks?

- Stimulation sites target different networks
- tDCS can alter functional connectivity between brain regions (Coffman et al., 2014), as demonstrated with fMRI and EEG
Overlapping Cognitive Skills?

• Enhancement of explicit learning with tDCS correlates with enhancement of attention (Coffman et al., 2012)
• Enhancement of working memory with tDCS mediated by enhancement of selective attention (Gladwin et al., 2012)
• Learning (memory acquisition/consolidation) linked to working memory and attention (Coffman et al., 2014)
Net zero-sum?

- Net zero-sum derived from notion of conservation of energy
- A gain in function is accompanied by an equal loss of function
- Is brain enhancement a zero-sum game? (Brem et al., 2014)
  - Distribution of processing power
  - Trade-offs
Evidence for Zero-Sum

• Inter-hemispheric inhibition
  – Motor Learning
  – Attention

• Anodal tDCS increases tNAA locally, but decreases tNAA in the opposite hemisphere (Clark et al., 2011)
Evidence for Zero-Sum

• Enhancement of social cognition in women, but impairment in men

• In a study of numerical learning (Iuculano & Cohen Kadosh, 2013):
  – tDCS of the DLPFC enhanced automaticity, but impaired numerical learning
  – tDCS of the posterior parietal cortex enhances numerical learning, but impairs automaticity

• Negatively correlated networks (Brem et al., 2014; Fox et al., 2005)
Controversy about efficacy

• Meta-analysis of cognitive effects of tDCS (Horvath et al., 2015)
  – Included every study of the cognitive effects of tDCS among healthy adults
  – Cognitive tasks must be used by 2 or more groups
  – Included only studies of single session tDCS
  – Spanned executive function, memory, language, and other
  – No significant effects of any
Controversy about efficacy

- Of the 50 cognitive tasks replicated by 2 or more research groups, 35 include 2-3 papers
- Significant effects may exist for multiple-day tDCS regimens
  - E.g., overnight consolidation
- State-dependency?
Overview

• Evidence that tDCS can enhance:
  – Learning
  – Working memory
  – Attention
  – Language
  – Social Cognition
  – Complex problem-solving
• Enhancing consolidation of memories
• Mechanisms may involve glutamatergic signaling, and EEG frequencies
• State dependency of enhancement
• Involvement of diverse networks vs. overlapping cognitive functions
• Net zero-sum
  – Inter-hemispheric inhibition
  – Different populations
• Conflicting findings
• Ethical considerations
Sources Cited


