The effects of transcranial alternating current stimulation on memory performance in healthy adults: A systematic review

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1. Background & Research Questions

Whilst evidence suggests small, but significant modulatory effects of transcranial alternating current stimulation (tACS) on perception and cognition[1,2], it is unclear how effective tACS is at modulating memory specifically, and its underlying neural oscillations.

A review is yet to synthesise:

- Effects of tACS and different tACS parameters on **memory** modulation specifically.
- Effect of the applied **phase of stimulation** between two target regions on the direction of tACS effects.
- Effects of **tACS at the neural level**.
- tACS efficacy in relation to **study** (e.g., task difficulty) and **participant** (e.g., younger/older, high-/low-performers) **characteristics.**

Primary RQ	1. Does tACS modulate memory performance in healthy adults?
Secondary RQ	2. What is the correspondence between the effects of tACS on memory performance and on the oscillatory features of M/EEG recordings?

2. Methods

Search date: 27.05.20 (updated: 05.03.21). Databases searched from Jan 2000 – present.

Searched: PsycINFO (Ovid), Medline (Ovid), CINAHL Plus (EBSCO Host), Web of Science Core Collection, tDCS Database, The Cochrane Library, ProQuest Dissertations & Theses Global and Open Grey.

(1) ['tACS'] related terms 'AND' (2) a general ['cognition'] term 'OR' ['memory'] related terms.

Table 1. Eligibility criteria

	Inclusion criteria	Exclusion criteria
Participants	≥ 18 years.	Pre-defined health condition(s).
Intervention	Single or multi-session open-loop tACS (no DC offset) alone or combined with cognitive training.	
Comparator	Sham-tES group.	
Outcomes	Primary outcome: memory performance (1) ≤30 seconds (WM) and/or (2) >30 seconds (LTM).	
Trial design	Sham-tES controlled designs.	Case reports and review articles.

Methods continued…

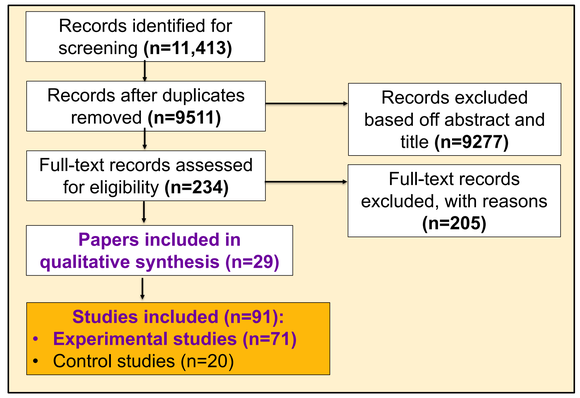

Figure 1. Search and selection PRISMA flowchart

Quality assessment:

- Performed independently by two reviewers using an adapted version of the Cochrane Risk of Bias Tool[3].

Data synthesis:

- **Narrative synthesis**: studies that were sufficiently similar were considered together.
- Developed our own criteria for evidence strength.

Table 2. Evidence strength

Evidence strength	Criteria
Strong	More than two-thirds of studies in agreement and more than 50% rated as having a low risk of bias.
Moderate	More than two-thirds of studies in agreement, but less than 50% rated as having a low risk of bias.
Weak	More than two-thirds of studies in agreement but methodological concerns that go beyond 'risk of bias' (e.g., small sample sizes etc.)
Insufficient evidence to conclude	All studies came from one paper, or evidence was very inconsistent (e.g., ~50% of studies reported significant modulation, whilst ~50% reported no-significant modulation) and quality assessments for the studies reporting significant and non-significant modulation were similar.

3. Results

Table 3. Summary characteristics

	Working memory	Long-term memory
Studies (N)	Experimental: n=58	Experimental: n=13
Frequencies	**Theta: 64%** Gamma: 19% *CF theta-gamma: 9% Alpha: 5% Beta: 3%	**Gamma: 46%** Theta: 23% *CF theta-gamma: 15% Beta: 15%
Montages	**Posterior: 38%** Anterior-posterior: 36% Anterior: 26%	**Anterior: 69%** Posterior: 31%

*CF-tACS (theta-gamma cross-frequency tACS): modulation of the power of a fast brain oscillation (e.g., gamma) by the phase of a slow rhythm (e.g., theta).

Working memory:

Posterior theta-tACS modulated ✓ **Strong evidence** — Most studies in agreement and most low risk of bias

- Inconclusive evidence: frontoparietal theta-tACS, beta-tACS and CF-tACS.
- Not effective: gamma-tACS (strong evidence), anterior theta-tACS (weak evidence) and alpha-tACS (weak evidence).

Long-term memory:

Anterior gamma-tACS modulated ✓ **Moderate evidence** — Studies in agreement but most unclear risk of bias

Anterior/posterior theta-tACS modulated ✓ **Strong evidence** — Studies in agreement and low risk of bias

- Inconclusive evidence: beta-tACS and CF-tACS.

Potential moderators:

- tACS significantly modulates performance at **high levels of cognitive demand** but not at lower levels.
- tACS effects are likely to depend on **individual variability in age and memory ability.**
- **In-phase tACS results in better memory performance** relative to sham.
- A **conclusion regarding the effects of anti-phase tACS is limited** by the inconsistency of the results in the evaluated literature.

Results continued…

Neural correlates:

- **Correspondence between memory performance and oscillatory outcomes at the stimulation frequency.**
- Frequency-specific effect of tACS on memory performance, where tACS modulates oscillatory features only at the stimulation frequency.

4. Discussion & Conclusion

Summary: small-to-medium effect of tACS on WM and LTM performance, though its efficacy depends on the stimulation frequency applied amongst other tACS parameters and/or study characteristics.

Limitations of the included literature:

- No description of double-blinding method provided.
- No paper was pre-registered.
- Many studies did not report effect sizes or the necessary information to calculate them.
- Many studies had small sample sizes and so were potentially underpowered.

Review limitations:

- List of potential moderators was not exhaustive.
- Future research might divide WM and LTM into sub-domains (e.g., visual, spatial etc.) or constituent components to evaluate whether tACS is better for some than for others.
- Heterogeneous nature of the studies restricted the ability to provide firm conclusions on the nature of tACS effects.

Acknowledgements & Funding

This review was conducted as part of a PhD funded by the Economic and Social Research Council (ESRC), awarded to Miss Samantha Booth. We would like to thank Freya Amsbury and Jayesha Chudasama for their contribution as second reviewers.

References

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Pre-registered: PROSPERO (CRD42020186449)

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