Transcranial Ultrasound Stimulation in Anterior Cingulate Cortex Impairs Information Sampling and Learning in Loss Contexts

Kianoush Banaie Boroujeni*[1], Michelle K Sigona[3,4], Robert Louie Treuting[4], Adrienne Hawkes[3,4], Charles F. Caskey[2,3,4], Thilo Womelsdorf*[1,4]

[1]Department of Psychology, Vanderbilt University, Nashville, TN 37240.
[2]Vanderbilt University Medical Center Department of Radiology and Radiological Sciences, Nashville, TN, USA.
[3]Vanderbilt University Institute of Imaging Science, Nashville, TN, USA.
[4]Department of Biomedical Engineering, Vanderbilt University, Nashville, TN 37240.

* kianoush.banaie.boroujeni@vanderbilt.edu

www.attention-circuits-control.org

VANDERBILT

VANDERBILT Vision Research Center

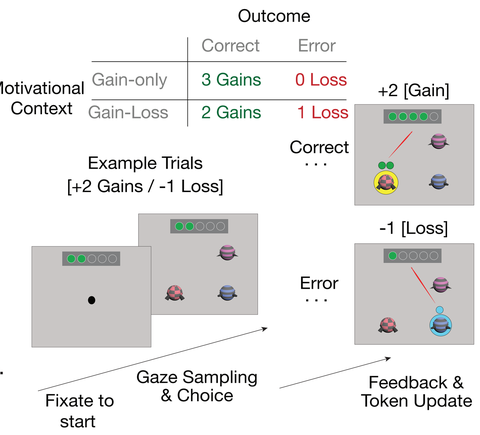
Introduction

The anterior cingulate cortex and the anterior striatum contain neural groups signaling how likely objects were paired with positive or aversive outcomes in the past, and which objects will be attended or visually sampled in the immediate future. Whether these neural signals play a causal role in guiding information sampling or motivating subjects to learn overcome aversive outcomes is unresolved. Here we tested these scenarios by transiently disrupting the anterior cingulate and the striatum with transcranial ultrasound while monkeys performed a learning task that independently varied attentional demands from motivational demands.

Experimental Design

- In each session, monkeys performed six baseline learning blocks of ~55 trials each.
- The task was a feature value learning task.
- In each learning block monkeys learned the feature associated with reward by trial and error.
- Blocks were orthogonally assigned to one of two *motivation contexts*, and one of the three *attentional loads.*

Motivational Context	Outcome: Correct	Outcome: Error
Gain-only	3 Gains	0 Loss
Gain-Loss	2 Gains	1 Loss

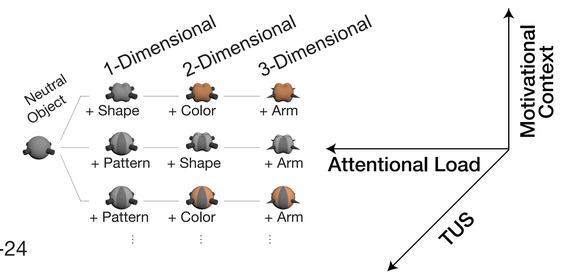


Motivational contexts are:

- Gain-only: 3 tokens gained for each correct choice.
- Gain-Loss: 2 tokens gained for each correct and 1 lost for each incorrect choice.

Attentional loads are:

- Number of feature dimensions on objects varying trial-by-trial.

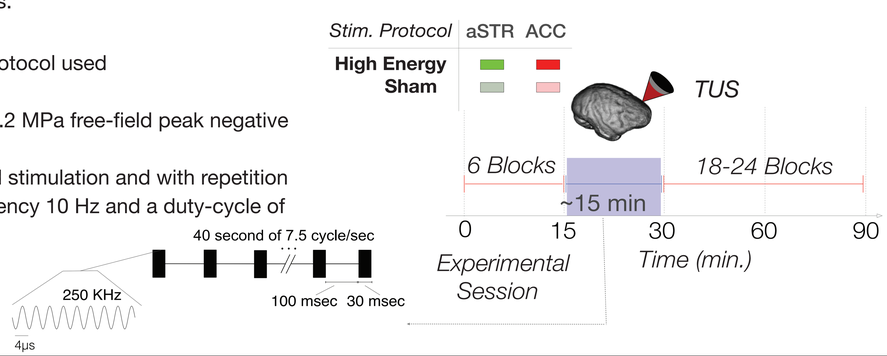


After 6 blocks the experiment was paused and TUS was applied on one of the areas:
- Anterior cingulate cortex (ACC)
- Anterior striatum (aSTR)

After TUS, experiment was resumed for 18-24 more blocks.

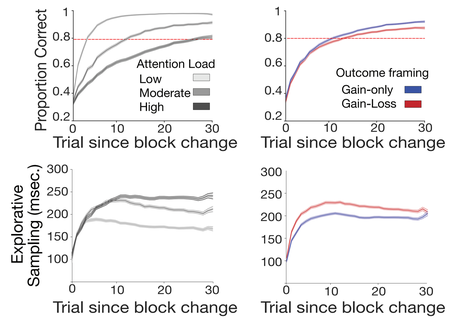
The TUS protocol used

- 250 kHz 1.2 MPa free-field peak negative pressure.
- 40 second stimulation and with repetition pulse frequency 10 Hz and a duty-cycle of 30%.

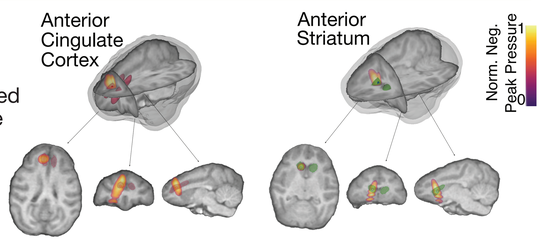


Effects of Motivational Contexts and Attentional Load on Learning and Information sampling

- Learning speed was measured by the trial number monkeys reached a learning criterion of 80% or more correct.
- Information sampling was measured as foveation duration onto objects before a choice.
- Monkeys showed longer foveation duration onto objects and slower learning in:
  - High attentional load
  - Gain-loss motivational context

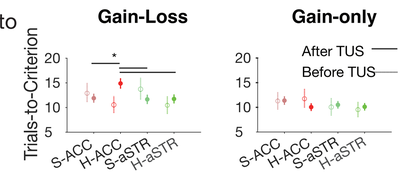


TUS in ACC impaired learning and prolonged information sampling

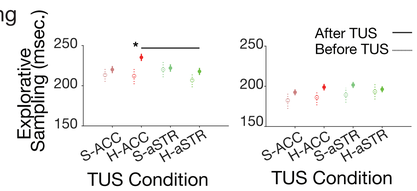


- Acoustic simulations showed the ACC and the aSTR were located within half max. peak pressure of TUS within the brain.

- ACC-TUS slowed down learning relative to baseline, aSTR-TUS, sham ACC-TUS, and sham aSTR-TUS in gain-loss but not gain-only conditions.

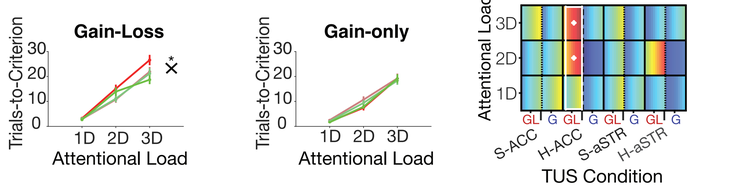


- ACC-TUS prolonged information sampling relative to baseline, and aSTR-TUS in gain-loss but not gain-only conditions.



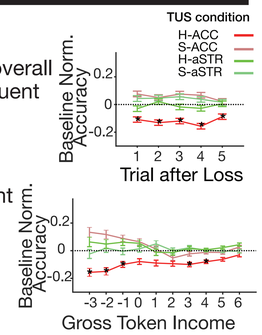
TUS-induced Learning Deficit Depends on High Attentional Load

- Observed TUS-ACC learning deficit in gain-loss learning context was limited to high attentional load.



TUS Impaired Post-error Adjustment After Loss

- Experiencing a loss leads to overall poorer performance in subsequent trials.
- Overall performance decrement was dependent on the recent history of losses.

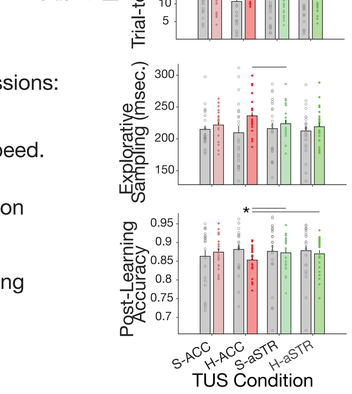


TUS Effects Were Evident Across sessions

- TUS-ACC changed behavioral metrics across sessions in gain-loss context.

TUS-ACC across sessions:

- reduced learning speed.
- prolonged information sampling.
- reduced post-learning accuracy.



Conclusions and Summary

- Transcranial ultrasound stimulation (TUS) of the anterior cingulate cortex disrupts learning from losses.
- The TUS-induced learning deficit depends on high attentional load.
- TUS impaired efficient fixational information sampling of objects during learning.
- Anterior cingulate cortex is causally supporting credit assignment of aversive outcomes to visual features.

References and Funding

This work was supported by the National Institute of Mental Health of the National Institutes of Health under Award Number **R01MH123687** and **1UF1NS107666.**

Shenhav, A., Botvinick, M. M. & Cohen, J. D. The Expected Value of Control: An Integrative Theory of Anterior Cingulate Cortex Function. Neuron 79, 217–240 (2013).

Monosov, I. E. & Rushworth, M. F. S. Interactions between ventrolateral prefrontal and anterior cingulate cortex during learning and behavioural change. Neuropsychopharmacol. 1–15 (2021) doi:10.1038/s41386-021-01079-2.