Testing a Cellular Metabolism Account of Attention and Capacity Limits in Perception

Merit Bruckmaier[1], Phong Phan[2], Ilias Tachtsidis[2], Nilli Lavie[1]

[1] Institute of Cognitive Neuroscience, University College London [2] Department of Medical Physics and Biomedical Engineering, University College London

Introduction

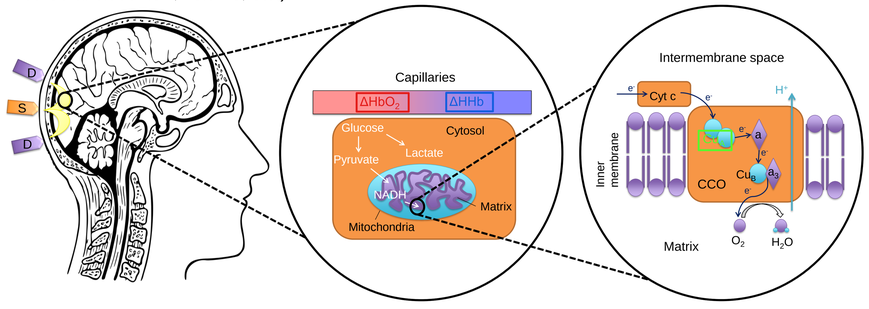
We propose that limited cerebral metabolic energy is the neurophysiological cause of perceptual capacity limits and that changes in neural energy usage and thus cellular metabolism underlie perceptual load modulations in the form of a metabolism trade-off between attended and unattended processing.

- The concept of a limited attention resource has been widely used to explain capacity limits in perception.
- In tasks of high perceptual load that exhaust the limited attention resource, unattended information no longer elicits a cortical response therefore resulting in “inattentional blindness” (e.g. Lavie et al., 2014).
- However, while the concept of a capacity limited attentional resource has been widely used to explain these modulations, it has not as yet been directly related to the cerebral cellular metabolism levels which are known as critical limiting factor on the energetically expensive neural response (Atwell & Laughlin, 2001; Clarke & Sokoloff, 1999; Sokoloff et al., 1955).
- Here we investigate an account that attributes capacity limits in perception to a direct impact of attention on the distribution of cellular metabolism to cortical regions responsive to attended vs. unattended stimuli.
- We predicted that increased perceptual load in a task should lead to increased cellular metabolism levels related to attended processing and a compensatory metabolism reduction for unattended processing.

Method

Broadband Near-Infrared Spectroscopy (BNIRS)

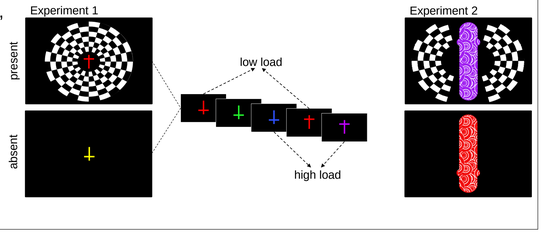
- We tested our account using BNIRS which allows us to measure cellular metabolism levels associated with visual processing via an intracellular marker of mitochondrial activity levels, unlike the fMRI BOLD signal which reflects blood oxygenation levels that are influenced by a wide range of factors (incl. cerebral blood flow, volume, etc.).



- BNIRS can measure concentration changes in oxygenated haemoglobin (HbO_2) and deoxygenated haemoglobin (HHb), as well as the oxidation state of the Copper A (Cu_A) redox site in the CCO enzyme (oxCCO) which forms part of the mitochondrial electron transport chain during oxidative phosphorylation.
- oxCCO is therefore an intracellular marker for the level of cellular oxygen metabolism which covers the majority of the increase in energy consumption during neural activity.

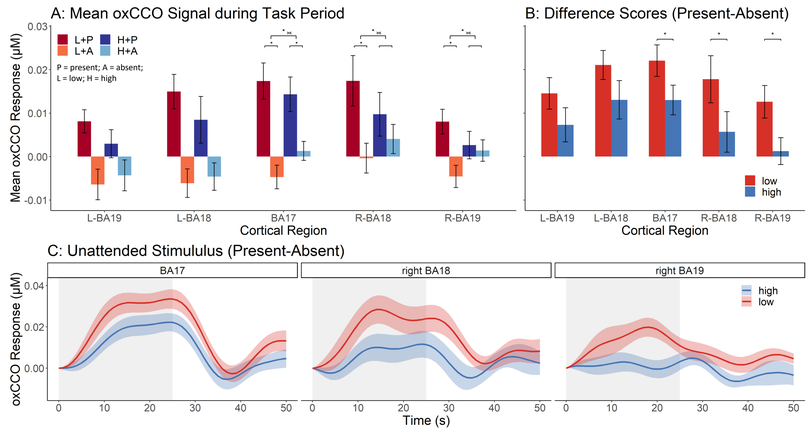
Experimental Task

- Across blocks, participants (N = 16 in E1, N = 18 in E2) responded either to high load (conjunction) targets or low load (feature) targets (in different blocks).
- On half of the blocks a task-irrelevant, flickering checkerboard distractor was present in the periphery.
- In E2, the size of the cross target was increased to be able to measure signals associated with attended processing.



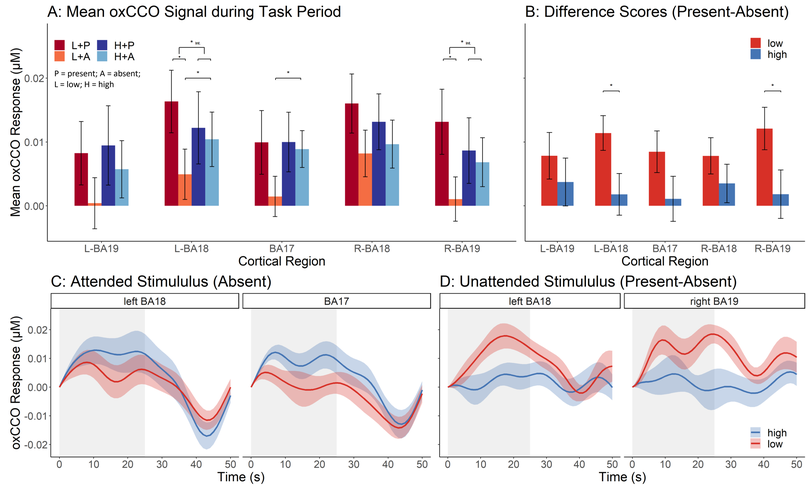
Results

Experiment 1: Perceptual load effect on metabolism underlying unattended processing



- Perceptual load affects oxCCO signal associated with unattended stimuli, as evidenced by the interaction between distractor presence (vs. absence) and perceptual load (high vs. low; Panel A)
- Metabolism signal in response to the presence of the unattended stimulus is reduced when perceptual load is high (Panel B).
- Load effects last throughout the 25 s task period (Panel C; grey, shaded area, followed by 25 s rest)

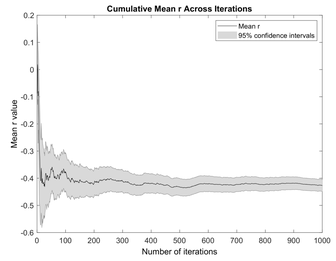
Experiment 2: Modulation of metabolism for attended and unattended processing under perceptual load



- Replication of interaction found in E1: oxCCO response to unattended signal is reduced by high perceptual load (Panels A, B, D).
- Attended oxCCO signal (absent conditions) is increased with high perceptual load (Panels A, C).

Load induced metabolism trade-off between attended and unattended processing in Experiment 2

- Second-by-second negative correlation between the group-averaged load effects on attended vs unattended processing is found in BA 18
- Mean r = -0.42, across 1000 random splits of data, to avoid shared variance in the two correlated time series since both included “distractor absent” trials; $p < 0.001$ as shown by a permutation test with 10,000 random permutations of the same data splits



Cumulative mean r value can be seen to stabilise on the resultant mean after ~150 random data splits

Summary and Conclusions

- Perceptual load affects the level of cellular metabolism in visual cortex regions responsive to attended and unattended stimuli
  - High perceptual load leads to a reduction in the oxCCO signal associated with unattended stimuli, while increasing the oxCCO signal associated with attended processing.
  - A negative temporal correlation of load effects on attended vs. unattended oxCCO levels supports our metabolism trade-off account.
- This provides evidence for our account that the frequently-theorized, capacity-limited mental resource corresponds to limited cellular metabolic energy across the brain, and that attention plays an important role in flexibly allocating these limited metabolism resources according to task demands.
- A localised resource trade-off allows to compensate for task-induced, metabolically expensive increases in neural firing.
- Our cerebral metabolism account can thus explain a wide range of neuroimaging and behavioural findings relating to capacity limitations and perceptual phenomena such as inattentional blindness.

References:

Attwell D, Laughlin SB (2001) An Energy Budget for Signaling in the Grey Matter of the Brain. J Cereb Blood Flow Metab 21:1133–1145.

Clarke D, Sokoloff L (1999) Circulation and Energy Metabolism of the Brain. In: Basic Neurochemistry: Molecular, Cellular and Medical Aspects., 6th ed. (Siegel G, Agranoff B, Albers R, Fisher S, Uhler M, eds), pp 637–669. Philadelphia: Lippincott-Raven.

Lavie N, Beck DM, Konstantinou N (2014) Blinded by the load: attention, awareness and the role of perceptual load. Philos Trans R Soc B Biol Sci 369:20130205.

Sokoloff L, Mangold R, Wechsler RL, Kennedey C, Kety SS (1955) The effect of mental arithmetic on cerebral circulation and metabolism. J Clin Invest 34:1101–1108.

Email: merit.bruckmaier.16@ucl.ac.uk
Phone: 0207 679 5372
Address: Merit Bruckmaier, Psychology and Language Sciences, 26 Bedford Way, WC1H 0AP, London, UK

TOYOTA
ESRC ECONOMIC & SOCIAL RESEARCH COUNCIL