Increased Midfrontal Theta-Band Power During an N-Back Task Following Working Memory Training

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Introduction

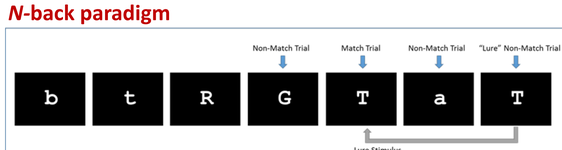
Working memory (WM) refers to a limited capacity system which enables the maintenance, updating and manipulation of information.[1] Individuals vary in their WM capacity, which has been shown to predict academic attainment above and beyond IQ.[2] WM has also been shown to be strongly correlated with fluid intelligence (G*f*).[3] A growing body of literature has examined the possibility that WM can be improved with targeted training; however, disagreement remains regarding the effectiveness of WM training. Neural correlates of WM training has previously been examined, including Event-Related Potentials (ERPs) and fMRI measures. However, the WM training literature has rarely examined neural oscillations. In the present study, we examine event-related oscillations (Event-Related Synchronization, ERS; or Event-Related Desynchronization, ERD) prior to and following WM training. Greater ERS in the theta (~4 – 8 Hz) band has been associated with better memory performance.[4] Theta ERS has also been observed in frontal electrodes during an n-back task, particularly following the presentation of target stimuli.[5] Greater ERD in the alpha (~8 - 15 Hz) has also positively associated with cognitive/memory performance,[4] and is observed in parietal electrodes during an n-back task, following the presentation of both target and non-target stimuli.[5] Parietal alpha ERD has also been associated with attentional networks and sensory semantic demands.[6]

Hypotheses

1. There will be a significant increase in frontal theta ERS during a verbal n-back task following WM training on an adaptive n-back task (but not following perceptual search training), in particular for target trials
2. There will be a significant increase in parietal alpha ERD during both a verbal n-back task,a spatial WM task (Spatial 3-back task, measuring transfer of training to WM in another domain) and a perceptual search task following both WM (n-back) and perceptual search training
3. There will be a significant increase in frontal theta ERS during a spatial n-back task following WM (n-back) training only

Methods

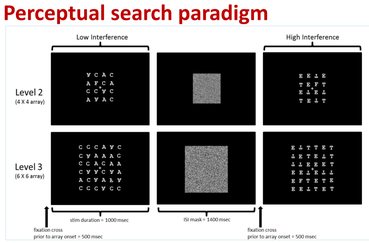
N-back paradigm



Task Parameters:
Stimuli: 10 letters of the English alphabet
Stimulus duration = 400 msec
Interstimulus Interval = 2,000 msec

Trial Types:
75 Match trials
100 Non-Match trials without lures
50 Lure trials (Non-Matches with lure stimuli)
10 Match trials with lures (not analyzed)

Perceptual search paradigm

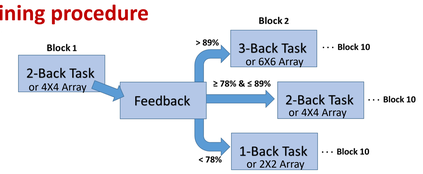


Task Parameters:
Stimuli: 10 letters of the English alphabet displayed in an array
Stimulus duration = 400 ms
Interstimulus Interval = 2,000 ms

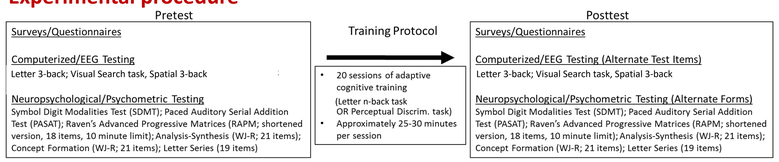
Trial Types:
75 Down F trials
100 Up F trials with low interference (Up F Reg)
50 Up F trials with high interference (Up F Int)
10 Down F trials with high interference (not analyzed)

Adaptive *n*-back or perceptual search training procedure

Participants completed approximately 20 sessions of n-back or perceptual search training, 5 days a week, for 25-30 minutes a day. Each session had 10 blocks of stimuli presented (45 + n trials per block, stim duration = 400 ms, ISI = 2,000 ms; Match or Down F trials = 33%, Non-Match or Up F Reg trials = 66.6% (22.2% of which were Non-Match Lure or Up F Int trials). Task progression was adaptively adjusted (see Figure on the right).



Experimental procedure

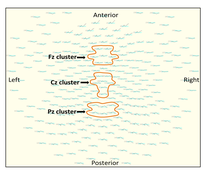


EEG time-frequency analysis

Acquisition: 256-channel HydroCel Geodesic Sensor Net (Electrical Geodesics, Inc., Eugene OR). Impedances were kept below 50 kΩ whenever possible. EEG data filtered between 0.1 to 100 Hz, digitized at 250 Hz. Vertex (Cz) served as the reference during data acquisition.

EEG Data Processing:
- 1 Hz high-pass filter & 50 Hz low-pass filter
- Data cleaning: clean_rawdata to remove bad channels, Artifact Subspace Reconstruction (ASR) to correct continuous data
- Channel interpolation
- Re-reference to average reference
- Epoch segmentation: -1000 to 1400 ms locked to stimulus onset (stimulus window: 0 to 400 ms)
- Epoch rejection: extreme values (-500 to 500 µV), improbability test (6 SD for single channels, 2 SD for all channels)
- Independent Component Analysis (ICA; runica using pca option)
- Independent Component (IC) Rejection: IClabel (1st 70 IC maps inspected)
- Baseline subtraction (pop_rembase; -200 to 0 ms)
- Trial type extraction (separate files for Match (or Down F), Non-Match (or Up F Reg) and Lure (or Up F Int) trials)

Time-Frequency decomposition:
- Trial type files for each subject and session underwent a complex Morlet wavelet convolution, implement using the Fast Fourier Transform (FFT)
  - Parameters: min freq: 3 Hz, max freq: 30 Hz, number of freq: 40, range of cycles: varied from 4 to 10
  - Baseline normalization: percent signal change using a baseline window of -400 to -100 ms
- Electrode clusters are defined according to the 10-20 electrode location system.[7] Note that only the Fz and Pz clusters were of interest in this analysis.
- Group files were used to create grand-averaged time-frequency plots
- Group files were also used to extract the change in power relative to baseline for each subject (max. rel. pow. decr., % ERD, for alpha range and max. rel. pow. incr., % ERS for theta range)
- Time window for extraction: 0 to 500 ms locked to stimulus onset
- Frequency windows: 4-8 Hz and 8-15 Hz
- Power values collected from each electrode within each of the Fz and Pz clusters were then averaged



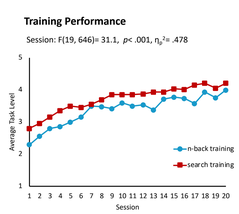
Results

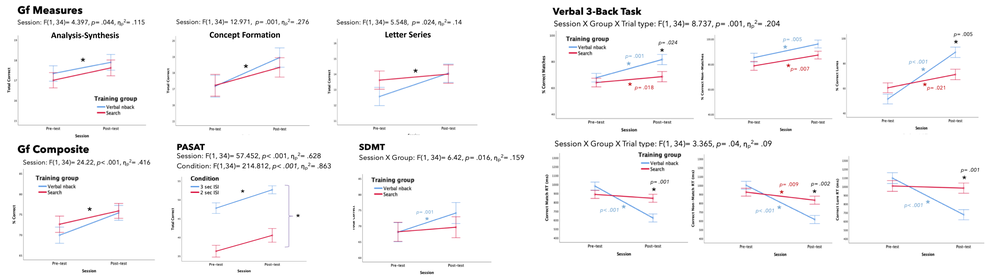
1. Demographics

Demographic variable	N-back Training (n = 18)		Search Training (n = 18)	
	M	SD	M	SD
Age (years)	24.28	4.13	24.33	4.56
Education (years)	17.00	2.11	16.56	1.82
Estimated full scale IQ	105.48	7.85	111.24[a]	9.34[a]
Gender (% female)	72.22%		72.22%	
Handedness (% right-handed)	94.44%		94.44%	

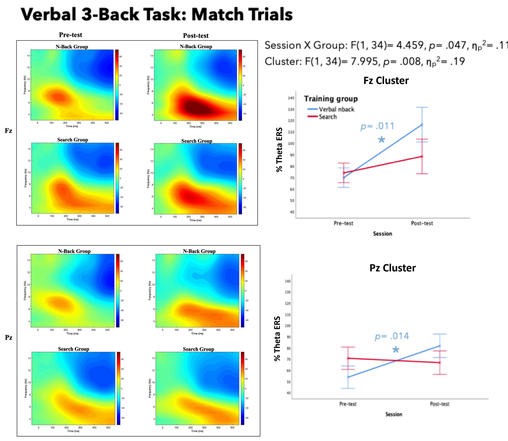
M: mean; SD: standard deviation
a. Estimated full scale IQ information missing for 1 of the search training participants; n= 17 for these values

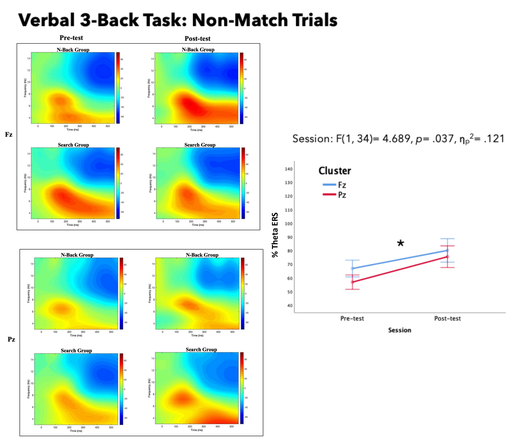
2. Behavioral Analyses

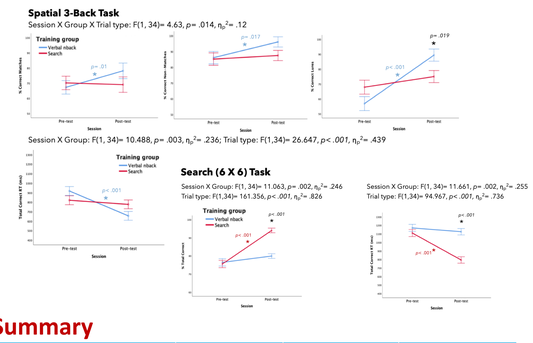


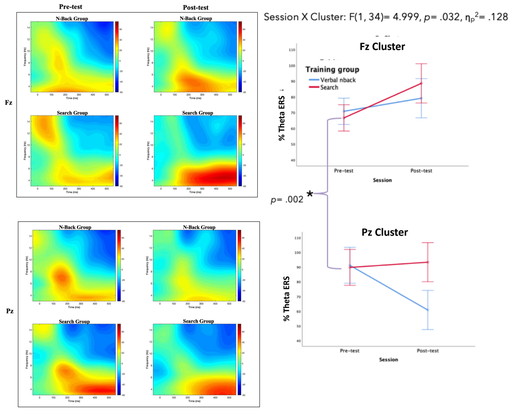


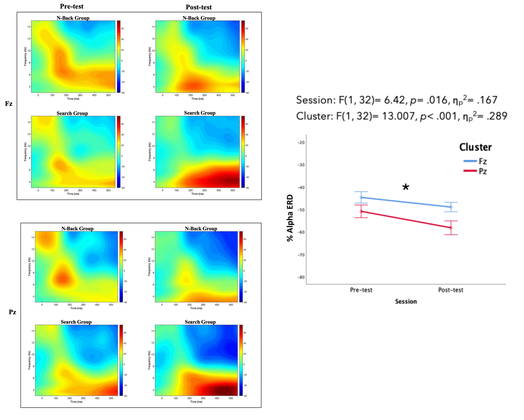
3. Time-Frequency Analyses

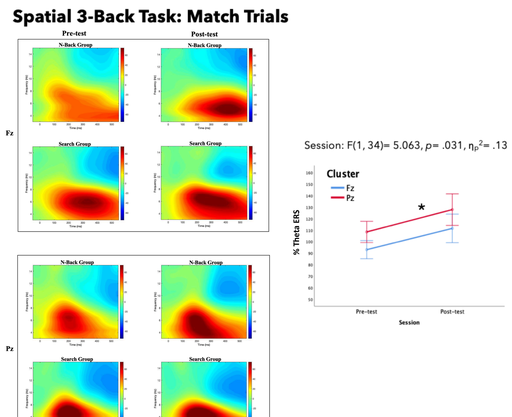


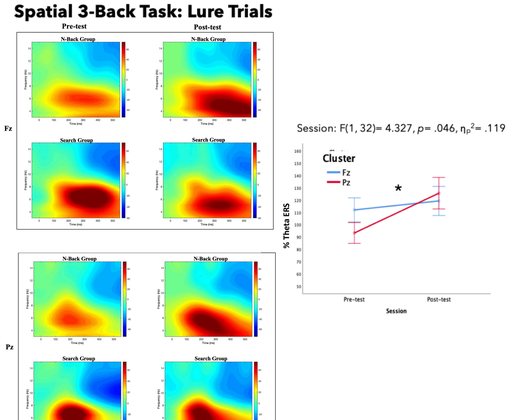












Statistics
1. Demographics: independent samples t-tests or chi-square analyses
2. Behavioral: Repeated Measures (RM) ANOVAs [Session (pre, post) X Group (n-back, search) X Trial Type (Match or Down F, Non-Match or Up F Reg, Lure or Up F Int)
3. Time-frequency: RM ANOVAs [Session X Group X Cluster (Fz, Pz)]. Only effects involving Session or Group are reported.

4. Summary

		Verbal 3-Back	Search	Spatial 3-Back
Match (or Down F) Trials	Theta ERS	n-back* > search	*Pz > Fz at pre-test*	n-back = search
	Alpha ERD			
Non-Match (or Up F Reg) Trials	Theta ERS	n-back = search		
	Alpha ERD			
Lure (or Up F Int) Trials	Theta ERS			n-back = search
	Alpha ERD		n-back = search	

- Confirming our hypothesis, there was a significant increase in theta ERS during Match trials in the Verbal 3-back task following training, for the n-back group only
  - This increase was not specific to the Fz cluster
  - As well, both groups improved on the Non-Match trials
  - These findings align with the behavioral findings
- Contrary to what was predicted, parietal alpha ERD did not increase for all tasks
  - The only alpha ERD effect found was an increase at post-test for Up F Int trials during the Search task (for both groups)
- Also contrary to what was predicted, both the n-back and search groups showed increased theta ERS following training (for Match and Lure trials)
  - This differs from behavioral findings, in which only the n-back group showed significant improvement on the Spatial 3-back
  - However, both groups did show equal improvement on other measures of near-transfer (PASAT) and on measures of far transfer (G*f* measures)

Conclusion & Further Analyses

- WM training is accompanied by increased theta ERS, suggesting that training may modify oscillatory mechanisms involved in WM
- Although theta ERS findings for the Verbal 3-Back were as expected and corresponded well with behavioral findings, this was not the case for the Spatial 3-back
  - For the Spatial 3-back, both groups showed increased theta ERS at post-test whereas only the n-back group showed improvement on the task
  - This suggest that training-induced changes in oscillatory activity may not necessarily correspond to task performance, particularly on an untrained task
  - Further, theta ERS may also be modulated by intensive attention training, even in the absence of WM demands
- The lack of alpha ERD effects suggests that the power during the baseline period maybe have already been relatively low
  - This is corroborated by the fact that ERS values were generally much greater than ERD values
  - An earlier baseline period, or a baseline period corresponding to a resting EEG period prior to testing, may have resulted in alpha ERD effects
- Further analyses examining correlations between ERS/ERD measures and task performance as well as neuropsychological test scores may help to untangle these relationships

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