Verbal Working Memory
Sternberg Verbal Working Memory Task

Encoding Phase: X J F Q V C

Maintenance Phase: Remember (Rehearse) Letters

Retrieval Phase: Decide if Probe Matches a Letter

High Load: 6 letters
Low Load: 1-3 letters
Advantages of Task

• Can examine activation during different phases of the task
• **Parametric modulation** is possible, i.e., we can vary the working memory load, e.g.,
  – High Load = 6 letters
  – Low Load = 2 letters
  – Can then do a High - Low contrast
    • The subject is doing the same task in High and Low conditions, which is better controlled than using Rest or other task for the control condition
Working Memory in Action

Chocolate Cake

Ingredients:
- 1 cup sugar
- 1/2 cup cocoa powder
- 2 cups flour
- 1/2 tsp baking powder
- 1/2 tsp baking soda
- 1 cup milk
- 1/2 cup vegetable oil
- 2 eggs
- 1 tsp vanilla extract

Method:
1. Preheat oven to 350°F (175°C).
2. In a large bowl, beat together the sugar, cocoa, flour, baking powder, and baking soda.
3. Add the milk, oil, eggs, and vanilla extract, and mix well.
4. Pour the batter into a greased 9x9 inch baking pan.
5. Bake for 25-30 minutes or until a toothpick inserted in the center comes out clean.
Verbal Working Memory in Action
Verbal Working Memory

Frontal

articulatory control system

Temporality-Parietal

phonological store

phonological loop

Baddeley Model of Verbal Working Memory
Cerebellar Contribution to This System?

Frontal

articulatory control system

phonological loop

Temporal-Parietal

phonological store
Cortico-Ponto-Cerebellar circuitry

Cortico-ponto-cerebellar Anatomy

Schmahmann, 1996

Brodal, 1979
Cortico-Ponto-Cerebellar Circuitry: Summary

Neocortex → Frontal

Pontine Nuclei → Temporal-Parietal

Cerebellar Cortex → Medial PN, Lateral PN

Superior Inferior
Stimulus Timing: Working Memory

High Load

(X J F) + (Q V C) 1.5 s 5.0 sec 1.0 s 0.5 s
Read 6 Letters Remember 6 Letters Respond if probe is a match

Low Load

R P W + L (K) X 1.5 s 5.0 sec 1.0 s 0.5 s
Read 1 Letter Remember 1 Letter Respond if probe is a match
Predicted Activations: Working Memory Task

Articulatory Control System

Frontal

phonological loop

Temporal-Parietal

Neocortex

Pontine Nuclei

Cerebellar Cortex

Phonological Store

Medial PN

Lateral PN

Superior

Inferior
Predicted Activations: Working Memory Task

Articulatory Control System

Phonological Store

Frontal

Temporal-Parietal

Neocortex

Pontine Nuclei

Cerebellar Cortex

Medial PN

Lateral PN

Superior

Inferior
Stimulus Timing: Motoric Rehearsal

**High Load**

(M K S) + (H Z Q)

1.35 s

Read 6 Letters

0.275 s

Follow instructions

**Low Load**

(B) R L + N G D

1.35 s

Read 1 Letter

0.275 s

Follow instructions
Predicted Activations: Motoric Rehearsal Task

Articulatory Control System

Phonological Store

Frontal

phonological loop

Temporal-Parietal

Medial PN

Lateral PN

Superior

Inferior

Neocortex

Pontine Nuclei

Cerebellar Cortex
Predicted Activations: Motoric Rehearsal Task

Articulatory Control System

Phonological Store

Frontal

phonological loop

Temporal-Parietal

Neocortex

Pontine Nuclei

Cerebellar Cortex

Medial PN

Lateral PN

Superior

Inferior
Cerebro-Cerebellar Activations: With vs Without Phonological Storage

During Which Phase(s) of the Trial Does Cerebellar Activation Occur
Sternberg Verbal Working Memory Task

Encoding Phase
- X J F Q V C
- Read Letters
- Sensory Acquisition
- Articulatory Preparation

Maintenance Phase
- Remember (Rehearse) Letters
- Articulatory Motor Control
- Error Correction
- Refreshment of Phonological Store

Retrieval Phase
- Decide if Probe Matches a Letter
- Executive Search, Comparison, Response Selection
- f
Distinguishing Trial Events

- Encoding: 2s
- Maintenance: 4s
- Retrieval: 3s

Simulation Responses to Single Events

Simulation Responses to Combined Events
Analysis of Phase-Dependent Activations

Temporal Specificity + Load Effect = Response to Phase

Encode + = Encoding Response

Maintain + = Maintenance Response

Retrieve + = Retrieval Response

(2 vs. 6 letters)
Left Frontal / Right Superior Cerebellar Concordance

Left Temporal-Parietal / Right Inferior Cerebellar Concordance

Summary

- Neuroanatomical connections and patterns of functional neuroimaging suggest two cerebro-cerebellar circuits participating in two subsystems of verbal working memory
  - Left frontal/right superior cerebellum linked to articulatory control system
  - Left inferior parietal/right inferior cerebellum linked to phonological storage
Sternberg Verbal Working Memory Task

**Encoding Phase**
- Sensory Acquisition
- Articulatory Preparation
- Read Letters

**Maintenance Phase**
- Articulatory Motor Control
- Error Correction
- Refreshment of Phonological Store
- Remember (Rehearse) Letters

**Retrieval Phase**
- Executive Search, Comparison, Response Selection
- Decide if Probe Matches a Letter
- f
fMRI Experiment
Auditory vs Visual Encoding

**Visual**

- Encoding: + Y S H R F M
- Maintenance: h
- Retrieval: yes no
- Next Trial: + K

**Auditory**

- Encoding: + Y S H R F M
- Maintenance: h
- Retrieval: yes no
- Next Trial: + M
Auditory/Visual Activations

Cerebro-Cerebellar Activation During Auditory Discrimination

Pediatric Cerebellar Tumor Patients

Cerebellar Patients

• 12 Children who had undergone surgical resection for a cerebellar pilocytic astrocytoma
  – No radiotherapy or chemotherapy
  – Mean age 12.5 (range 6-19)
  – Tested 5.5 +/- 3.1 (SD) years post-surgery

• 12 controls matched on gender, age, and education level
Cerebellar Patients Have Decreased Digit Span With Auditory Presentation of Items

Verbal Working Memory Deficit from a Cerebellar Lesion

Cerebellar damage produces selective deficits in verbal working memory

Susan M. Ravizza,  Cristin A. McCormick,  John E. Schloer,  Timothy Justice,  Richard B. Ivey  and Julie A. Fiez  

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The cerebellum is often active in imaging studies of verbal working memory, consistent with a putative role in articulatory rehearsal. While patients with cerebellar damage occasionally exhibit a mild impairment on standard neuropsychological tests of working memory, these tests are not diagnostic for exploring these processes in detail. The current study was designed to determine whether damage to the cerebellum is associated with impairments on a range of verbal working memory tasks, and if so, under what circumstances. Moreover, we assessed the hypothesis that these impairments are related to impaired rehearsal mechanisms. Patients with damage to the cerebellum (n = 14) exhibited a selective deficit in verbal working memory: spatial forward and backward spans were normal, but forward and backward verbal spans were lower than controls. While the differences were significant, digit spans were relatively preserved, especially in comparison to the dramatic reductions typically observed in classic short-term memory patients with parietal brain damage. The patients tended to be more impaired on a verbal version compared to a spatial version of a working memory task with a long delay and this impairment was correlated with overall symptoms and dysarthria severity. These results are consistent with a contribution of the cerebellum to rehearsal and suggest that inclusion of a delay before recall is especially detrimental in individuals with cerebellar damage. However, when we examined markers of rehearsal (i.e. word-length and articulatory suppression effects) in an immediate serial recall task, we found that qualitative aspects of the patients’ rehearsal strategies were unaffected. We propose that the cerebellum may contribute to verbal working memory during the initial phonological encoding and/or by strengthening memory traces rather than by fundamentally subserving articulatory rehearsal.

Keywords: verbal working memory; cerebellum; dysarthria; spatial memory

Abbreviations: SMA = supplementary motor area

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Introduction

Working memory—the ability to maintain task-relevant information in mind—is achieved through the engagement of a widely distributed network of cortical and subcortical areas. Regions within the frontal and parietal cortices as well as the cerebellum consistently show increased activation in neuroimaging studies of working memory and much research has been dedicated to exploring the functional contribution of these regions (Patterson et al., 1995; Schumacher et al., 1996; Jacobs et al., 1997; Haxby et al., 2000; Gabrieli et al., 2003; Corbetta & Shulman, 2002; Haxby & Gobbini et al., 1999, ventral lateral prefrontal (VLPFC; BA 45; Thompson-Schill et al., 2000), and superior parietal cortices (BA 7; Marinkovic et al., 2000) are thought to support domain general processes important for working memory (such as updating items and maintaining sequential order), whereas the right and left

Fig. 2 Largest list length that control participants and cerebellar patients were able to recall (forwards and backwards) in the digit and spatial span tests of Experiment 1.
Working Memory and Verbal Fluency Deficits Following Cerebellar Lesions: Relation to Interindividual Differences in Patient Variables

Jutta Peterburs · Christian Bellebaum · Henno Koch · Michael Schwarz · Irene Daum

Published online: 13 April 2010
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Abstract Findings concerning cognitive impairment in patients with focal cerebellar lesions tend to be inconsistent and usually reflect a mild deficit. Patient variables such as lesion age and the age at lesion onset might affect functional reorganization and contribute to the variability of the findings. To assess this issue, 14 patients with focal vascular cerebellar lesions and 14 matched healthy control subjects performed a verbal working memory and a verbal long-term memory task as well as verbal fluency tasks. Patients showed deficits in working memory and verbal fluency, while recall of complex narrative material was intact. Verbal fluency performance correlated significantly with age in the patient group, with more severe impairments in older patients, suggesting that age at lesion onset is a critical variable for cognitive outcome. In controls, no significant correlations with age were observed. Taken together, our findings support the idea of cerebellar involvement in nonmotor functions and indicate the relevance of interindividual differences in regard to clinical parameters after focal cerebellar damage.

Keywords Cerebellum · Working memory · Cognition · Verbal fluency · Age · Functional reorganization

Introduction

Over the past two decades, an increasing number of studies has addressed the issue of cerebellar contributions to nonmotor functions [1] (for a review), 2, with cortico-ponto-cerebellar and cerebellar-thalamo-cortical loops serving as the anatomical correlates [3, 4]. In line with this notion, neuropsychological studies of patients with cerebellar damage have shown impairments of executive functions such as verbal fluency [5, 6], error detection [4], verbal working memory [7–9] and planning [10], nonmotor associative learning [11, 12], memory [13], spatial attention [14, 15], linguistic abilities [16] and emotion regulation [17, 18]. Functional neuroimaging has corroborated these findings by reliably showing cerebellar activations across a range of cognitive tasks, e.g., requiring covert word generation [19] or focused attention [20] and verbal working memory in particular [21–24]. Cerebellar activations during verbal working memory tasks presumably reflect rehearsal mechanisms [25, 26].

As a general pattern, cognitive impairment after selective cerebellar damage tends to be mild or cannot be replicated reliably across studies [1, 27], with the presence of extracerebellar damage or motor demands being critical variables [27]. Further important issues in ischemia patients are age at lesion onset and time since lesion onset, with intact performance in chronic lesion patients being at least partly due to reorganization mechanisms, although the empirical evidence is as yet sparse. Functional reorganization has been shown to play an important role for certain brain structures and cognitive domains. A recent study by Braun et al. [28] illustrates that functional reorganization may explain some of the divergent findings of associative memory impairments in patients with hippocampal damage.

Age at lesion onset is an important determinant of
Ziemus et al (2007)

- Found digit span deficits in cerebellar stroke patients
- Also performed 2-back verbal working memory in these patients during fMRI
Ziemus et al (2007)

- Increased activation in patients during verbal working memory was found in bilateral parietal cortex, suggesting compensation for the loss of cerebellum.

Activation shows 2-back vs 0-back in patients > 2-back vs 0-back in controls.
Quantifying Lobular Damage
# Left HVIII Damage Correlated with Auditory Digit Span

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<th>Left DN</th>
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</table>

*Less than 5% of lobule resected; + 5-50% of lobule resected; ++ more than 50% of lobule resected*

### Dependent vs. Fitted

![Dependent vs. Fitted Graph](image1)

![Dependent vs. Fitted Graph](image2)

**Schmahmann et al. (2000) MRI Atlas of the Human Cerebellum**

**-64 R**

**Lobule VIII**
Case Study: Left Lobule VIII / Right Lobule V Damage
Auditory Verbal Working Memory Deficits

Chiricozzi et al. (2008) *Neuropsychologia* 46, 1940-1953
Post-encoding TMS Administration

- **Encoding**: 1.5 seconds
- **Maintenance**: 4 seconds
- **Retrieval**: 0.8 seconds

Identify presented letter X J F Q V C

Identify presented letter k b r f
Targeting Cerebellar Activation

Surface Landmarks

TMS Coil Positioning

Tragus

Inion
TMS Targeting: Subject-Specific Localization of Right Superior Cerebellar Activation Obtained from Verbal Working Memory Task

Posterior View of Cerebellum for 5 subjects
Tasks

1. Verbal Working Memory
   - X J F Q V C
   - 1.5 s
   - 4.0 s
   - 0.8 s
   - 2.5 s
   - TMS Stim (50% of trials)
   - Identify presented letter

2. Verbal Working Memory (Sham Coil)
   - X J F Q V C
   - 1.5 s
   - 4.0 s
   - 0.8 s
   - 2.5 s
   - Sham Stim (50% of trials)
   - Identify presented letter

3. Motor Control
   - # # # # # #
   - 1.5 s
   - 4.0 s
   - 0.8 s
   - 2.5 s
   - TMS Stim (50% of trials)
   - Identify the “x”

TMS Effects on Reaction Time

Motor vs Cognitive RT Effects from Cerebellar TMS

Interpretation and a Question

• Superior cerebellar TMS disrupts normal encoding function of cerebellum, thereby making it more difficult to subsequently utilize the information (increased RT)

• If disease compromises cerebro-cerebellar circuitry thereby making the task more difficult, how will brain activation respond?
Effects of Chronic Alcohol Consumption on Verbal Working Memory

- Why? Alcohol is known to affect cerebellum as well as neocortical regions
Cortical Gray and White Matter Volumes

Alcoholic

57 yr old men

Lifetime consumption of alcohol
1866 kg

Control

57 yr old men

Lifetime consumption of alcohol
60 kg

Pfefferbaum et al. (1997)
Left Hemisphere Tests: Men

Sullivan et al., ACER 2000
Behavioral Results

**Accuracy**

- **High Load**: control, alcohol
- **Low Load**: control, alcohol

Both show no significant differences (n.s.), indicating similar accuracy levels for alcohol and control groups.

**Reaction Time**

- **High Load**: control, alcohol
- **Low Load**: control, alcohol

Both show no significant differences (n.s.), indicating similar reaction times for alcohol and control groups.
Alcoholic > Non-Alcoholic: Verbal Working Memory

Left Prefrontal

Right Cerebellum

Desmond, Chen, DeRosa, Pryor, Pfefferbaum, & Sullivan (2003), *Neuroimage, 19, 1510-1520*
Interpretation

• This fronto-cerebellar system is working harder in alcohol-dependent individuals to maintain performance comparable to controls
Encoding Activation: Sensory Acquisition?

• Does the cerebellar load activation found during encoding reflect greater sensory acquisition demands for High Load relative to Low Load?
Manipulating Sensory Acquisition Demands

Luminence corrected
### Varying Sensory and Articulatory Demands

#### Articulatory Demand

<table>
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<tr>
<th>Sensory Demand</th>
<th>High (4 Letters)</th>
<th>Low (2 letters)</th>
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<tr>
<td>High (Degr)</td>
<td>CMJX</td>
<td>X%R%</td>
</tr>
<tr>
<td>Low (Non-Degr)</td>
<td>MWLZ</td>
<td>%ZW%</td>
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</table>
Strategy (Liang et al, 2018)

• Step One: First define cerebellar regions of interest (ROIs) based on High Load – Low Load Contrast

• Step Two: Test those regions to see if the Degraded – NonDegraded contrast is significant
Step One Results

Load Effect During Encoding of Letters
High Load > Low Load

Z = -26

L HVI
Vermis Crus II
R HVI

Regions of Interest
Based on High vs Low Contrast

L HVI
Anterior
Y = -59
Y = -63
Y = -66
Y = -69
Y = -72
Y = -76
Posterior

R HVI

Vermis Crus II
Step Two Results

Greater Sensory Acquisition Demands For Degraded Stimuli

Degraded > Non-degraded

Inf Occip gyr
Fusiform gyr

High Load > Low Load

Degr > Non-Degr Small Volume Correction

<table>
<thead>
<tr>
<th>ROI</th>
<th>FWE-corr</th>
<th>FDR-corr</th>
<th>T</th>
<th>Uncorr</th>
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<td></td>
<td>No suprathreshold clusters</td>
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<tr>
<td>L Hem Lob VI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No suprathreshold clusters</td>
</tr>
</tbody>
</table>

Common Vermis Activation

High Load > Low Load  Degraded > Non-degraded
Discussion

• Sensory acquisition demands were increased by degrading the stimuli, as seen by the increased visual cortical activation

• Eye movements were recorded during the scan, and did not differ for high load vs low load, or for degraded vs non-degraded stimuli

• The vermis, but not the hemisphere ROIs exhibited Degraded > NonDegraded activation
Conclusions

• To explain these findings, an overall function of forward model prediction may underlie general cerebellar function, with perceptual prediction of stimuli from partial representations occurring in the vermis, and prediction of impending articulatory rehearsal occurring in the hemispheres.
Sternberg Verbal Working Memory Task

Encoding Phase
- Read Letters
  - Sensory Acquisition
  - Articulatory Preparation

Maintenance Phase
- Remember (Rehearse) Letters
  - Articulatory Motor Control
  - Error Correction
  - Refreshment of Phonological Store

Retrieval Phase
- Decide if Probe Matches a Letter
  - Executive Search, Comparison, Response Selection
Phonological Similarity Effect

**Phonologically Similar**

<table>
<thead>
<tr>
<th>Encoding</th>
<th>Maintenance</th>
<th>Retrieval</th>
<th>Next Trial</th>
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</thead>
<tbody>
<tr>
<td>+ B D G P T V</td>
<td>C yes no</td>
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**Phonologically Dissimilar**

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<td>+ F Q Z X W R</td>
<td>k yes no</td>
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Phonological Similarity Effect

- Phonologically similar words or letters are more difficult to remember than phonologically dissimilar words/letters.
- Patients with left temporal/parietal lesions have equally poor verbal working memory for phonologically similar and dissimilar words/letters, i.e., there is no phonological similarity effect.
Neural Substrates of Increasing Phonological Storage Demand
fMRI Verbal Working Memory Task

- **Fixation**: 3000-5000 ms
- **Encoding**: 1 letter/second
- **Maintenance**: 4000/6000 ms
- **Retrieval**: 3000 ms

**Similar**
- High load, repeating: C T Z G P
- Low load, repeating: C T
- High load, novel: V B C G P
- Low load, novel: Z V

**Dissimilar**
- High load, repeating: S F J Q N
- Low load, repeating: J Q
- High load, novel: H N F W S
- Low load, novel: N F

- Not Aware
- Linear Decr in RT

Peterburs et al., 2019
Maintenance Phase: High Load Trials

A. Right inferior cerebellum (lobule VIIIa)

Inferior cerebellum Sensitive to phonological Storage demand

Cerebellum sensitive to regularities of sequences in verbal working memory

Peterburs et al., 2019
Investigation of Phonological Similarity Effect: Cerebellar Patients

- Lesion patterns were examined for cerebellar subjects whose PSE was deviant from controls by > 3 SD
  - 3 subjects with abnormal PSE to aurally-presented stimuli
  - 3 different subjects with abnormal PSE to visually-presented stimuli
  - In both groups conjunctions of lesions were performed to determine if there was a region common to affected subjects
Lesions Disrupting Phonological Similarity Effect

Red regions represent conjunction of lesions for subjects exhibiting abnormal PSE.

Chiricozzi et al. cerebellar case study: Patient exhibited phonological storage deficits:

- Abnormal recency effect*
- Absence of phonological similarity effect to aurally-presented stimuli

*Recency effect: Normal healthy subjects tend to have better memory for the most recently presented item. This effect does not occur in patients with damage to the phonological storage system (left temporal/parietal lesioned patients).
Reduced phonological similarity effects in patients with damage
to the cerebellum

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Abstract

Three cerebellar patients were compared to 10 control subjects on a verbal working memory task in which the phonological similarity of the words to be remembered and their modality of presentation were manipulated. Cerebellar patients demonstrated a reduction of the phonological similarity effect relative to controls. Further, this reduction did not depend systematically upon the presentation modality. These results favor a model that qualitative differences in verbal working memory may be observed following cerebellar damage, indicating altered cognitive processing, even though behavioral output as measured by the digit span may be within normal limits. However, the results also present problems for the hypothesis that the cerebellar role is specifically associated with articulatory rehearsal as conceptualized in the Baddeley–Hitch model of working memory.

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1. Introduction

Researchers in cognitive neuroscience have in many cases looked to converging data from multiple methodologies when investigating a cognitive process of interest. The complementary perspectives of functional neuroimaging and cognitive neuropsychology are often employed in this regard: a strong case can be made for the involvement of a brain region in a given cognitive process when it is both metabolically active in healthy participants engaged in the cognitive process, and when damage to this region disrupts the same cognitive process. Although the precise nature of this involvement may prove elusive to characterize, the brain region comes to be regarded as an essential component of the system in question. When the two methodologies of neuroimaging and neuropsychology do not converge, however, even the most basic question of whether a given region is involved in a cognitive process is difficult to address.

One issue that must be kept in mind when making comparisons between data from neuroimaging and data from neuropsychology is that the two methods provide very different kinds of evidence about cognition. Neuroimaging studies have the potential to document qualitative aspects of cognitive processing that may not be evident from the behavioral outcome. In contrast, neuropsychological data—particularly that from standardized batteries that examine for gross impairment across a wide range of cognitive tasks—sometimes do not allow for such an observation. Identical behavioral outcomes may become falsely equated with identical cognitive processes, when this most cer-
Phonologically Similar and Dissimilar Word Lists

Table 3
Experimental stimuli for generating phonologically similar and dissimilar lists

<table>
<thead>
<tr>
<th>Initial consonant</th>
<th>Vowel</th>
<th>/i/</th>
<th>/e/</th>
<th>/E/</th>
<th>/ae/</th>
<th>/ɪ/</th>
<th>/I/</th>
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</thead>
<tbody>
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<td>bead</td>
<td>bathe</td>
<td>bell</td>
<td>back</td>
<td>bus</td>
<td>bin</td>
<td></td>
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<tr>
<td>/p/</td>
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<td>peg</td>
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<td>pun</td>
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<td></td>
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<td>mud</td>
<td>mill</td>
<td></td>
</tr>
<tr>
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<td>need</td>
<td>name</td>
<td>neck</td>
<td>nap</td>
<td>nut</td>
<td>knit</td>
<td></td>
</tr>
</tbody>
</table>

Results

Phonological similarity effect is strong in controls, and nearly absent in bilaterally damaged cerebellar patients.

Disrupting Cerebellar Prediction in Verbal Working Memory

• Inspired by Miall et al., 2007 study
• In that study, TMS was used to disrupt state estimation in the forward model of a hand trajectory
• An analogous design was used to disrupt the forward model of the “articulatory trajectory” of verbal working memory
Miall et al., 2007
Miall et al., 2007
Miall et al., 2007

A diagram showing a virtual target, a half-silvered mirror, and a target with a reaching movement and a lateral movement between 500 and 1500 ms.
Disrupting Cerebellar Prediction in Verbal Working Memory

Sheu et al. submitted
Disrupting Cerebellar Prediction in Verbal Working Memory

Sheu et al. submitted
Conclusions

• Cerebellar TMS caused more errors on early and correct probes, but not late probes, relative to occipital (control) TMS
  – Seemed to be using out of date information to predict the next letter in the sequence.

• This pattern of errors is consistent with TMS causing a temporary disruption of state estimation and cerebellar forward model function, leading to prediction errors in the phonological loop.
Sternberg Verbal Working Memory Task

Encoding Phase
- Read Letters
  - Sensory Acquisition
  - Articulatory Preparation

Maintenance Phase
- Remember (Rehearse) Letters
  - Articulatory Motor Control
  - Error Correction
  - Refreshment of Phonological Store

Retrieval Phase
- Decide if Probe Matches a Letter
  - Executive Search, Comparison, Response Selection

X J F Q V C
To be discussed in executive function lecture
Summary

• Encoding
  – Left posterior frontal / right superior cerebellum
  – Modality independent (but note L inf cerebellum)
  – Load dependent cerebellar activation cannot be universally explained by increased sensory acquisition demands
  – Disruption impairs performance; compensatory activation
Converging Evidence: Cerebro-Cerebellar Hyperactivation

Accuracy

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Alcohol</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>n.s.</td>
<td></td>
</tr>
</tbody>
</table>

Reaction Time

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Alcohol</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td>n.s.</td>
</tr>
</tbody>
</table>

Auditory Language Task: Alcohol > Control

Summary

• Encoding
  – Left posterior frontal / right superior cerebellum
  – Modality independent (but note L inf cerebellum)
  – Load dependent cerebellar activation cannot be universally explained by increased sensory acquisition demands
  – Disruption impairs performance; compensatory activation

• Maintenance
  – Left inferior parietal / right inferior cerebellum
    • Activation depends on phonological storage requirement
  – Activations enhanced by phonological similarity
    • But this activation decreases if there are sequence regularities
    • Inferior cerebellar damage impairs phonological similarity effect
  – Prediction used during rehearsal can be disrupted by cerebellar TMS

• Retrieval - To be discussed
The Role of the Cerebellum in Verbal Working Memory

• For rapid limb movements, the cerebellar forward model is hypothesized to compute a prediction of the limb trajectory.

• When a sequence of letters must be held in mind, an “articulatory trajectory” must be computed.
  – Analogous to a limb trajectory.
Hypothesized Functions

- **Forward model:** Rapid prediction of articulatory trajectory needed for phonological loop

Articulatory structures include: lips, cheeks, tongue, jaw, hard palate (roof of mouth), and soft palate (which has the velum, the soft tissue in back of throat, plus uvula, the small cone that hangs down)
Cerebro-Cerebellar Loops in Verbal Working Memory

Articulatory Control System

Frontal

Temporal-Parietal

phonological loop

Phonological Store

Thalamus

Med. PN

Lat. PN

Deep

Nucl

Sup. CBL

Inf. CBL

Left Temporal-Parietal / Right Inferior Cerebellar Concordance

Encoding 2 seconds

Maintenance 4 or 6 seconds

Retrieval 3 seconds

X J F

Q Y C

+ f Match?

Chen & Desmond, Neuropsychologia, 43: 1227-1237 (2005)
Hypothesized Functions

• Sensory prediction of the letter sequence that the phonological store will contain
Possible Forward Models in Verbal Working Memory

**Encoding Phase**
Frontal/Superior CBL

- Motor command
- Efference copy
- Motor system
- Musculo-skeletal system
- Motor output and sensory consequences
- Reafference
- Comparator
- Error signal
- Error signal updates models
- Forward dynamic model
- Predicted sensory consequences
- Corollary discharge

“QXVTWR” Articulatory trajectory

Prediction of mouth, tongue, lip movements and sensory consequences

**Maintenance Phase**
Parietal/Inferior CBL

- Motor command
- Efference copy
- Motor system
- Musculo-skeletal system
- Motor output and sensory consequences
- Reafference
- Comparator
- Error signal
- Error signal updates models
- Forward dynamic model
- Predicted sensory consequences
- Corollary discharge

Refresh phonological store

Prediction of the phonological stream

Facial/trigeminal systems
Cerebellar Contribution

• Net result of motor and sensory predictions: Increased efficiency and greater probability of success of the phonological loop