

The Cerebellum and Sensory Acquisition

Why is Cerebellum linked to control and coordination of movement?

- Correlation between relative size and complexity of cerebellum and animal's agility
- Particular lobules are expanded in relation to fine motor control systems in humans and other animals
- Cerebellar damage or disease produces deficits in motor control and coordination, but not perceptual deficits
- Neuronal activity in cerebellum is related to movements
- Cerebellar outputs go to known motor and premotor regions

Paulin: Evolutionary Analysis

- "...it has been said that because cerebellar dysfunction causes obvious deficits in control and coordination of movements, but no obvious deficits in sensation or perception, the function of the cerebellum is to control and coordinate movements."
- Equating the function of the cerebellum with the deficits that appear when it is damaged is logically unsound
 - "For example, when a stone shatters the windscreen on a car there may be obvious effects on the car's movements, but it would be a mistake to call the windscreen a 'motor control' device on this basis."

Paulin, M.G. (1993) *Brain, Behavior & Evolution* 41, 39-50.

Paulin

- Cerebellum arises from somatic sensory columns of the neural tube
- Cyclostomes (jawless fish)
 - Acousticolateralis medullary area filters signals related to water pressure, sound, and gravity
 - Its circuitry is nearly identical to that of the cerebellum



Paulin: Fish

- Teleosts (ray-finned fish)
 - Cerebellar lesion experiments yield contradictory evidence on role in movement control
 - Cerebellectomy disrupts ability to locate source of a particular sound

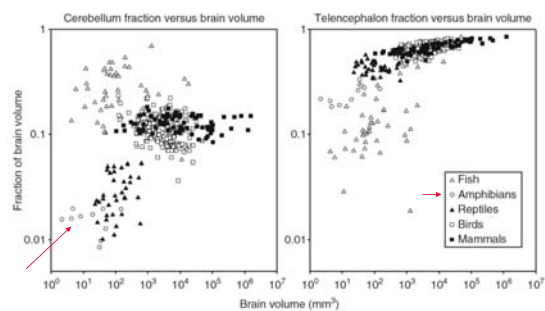


Paulin: Amphibians

- Cerebellum is small and simple compared to other vertebrates, including aquatic vertebrates, and has been regarded as primitive
- Inconsistent with the increased motor demands related to balance, posture, and movement when transitioning from water to land locomotion



Volume Fraction of Cerebellum and Telencephalon



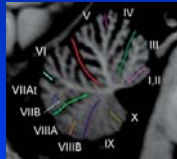
Paulin: Reptiles

- Locomotion in turtles involves “appendicular skeleton” rather than “axial skeleton”
- Medial cerebellum is reduced, consistent with lack of axial movements in locomotion
- However, there is also a lack of sensory innervation of the carapace (dorsal shell)
- In the Japanese soft-shell turtle, the carapace is very sensitive, and the medial cerebellum is enhanced (hypertrophied)



Paulin: Birds

- Hummingbirds are very agile
- Tails are critical for controlling and stabilizing flight, but have little sensory innervation
- Cerebellar lobules related to tail (I/II) are relatively underdeveloped



Paulin: Mammals

- Monotremes (egg layers like platypus)
 - Have very large cerebella, especially lobule VI
 - They have hypertrophied sensory trigeminal nerve and nucleus
 - In addition to tactile receptors, the beak is also electroreceptive and conveys this sense via the trigeminal nerve



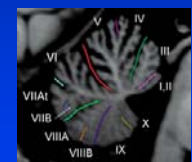
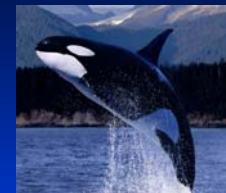
Paulin: Rodents

- Like platypus, trigeminal sensory input is also important, and cerebellar cortex responds to whisker and tactile cutaneous stimulation
- Rat trigeminal region is also associated with a complex motor system to control jaw, lips, tongue
 - in contrast to platypus, which has a very rigid beak
- The similarly enlarged cerebellar regions in both species seems to be more associated with sensory requirements rather than motor demands



Paulin: Cetaceans (whales, dolphins, porpoises)

- Vermal lobule VIII is greatly expanded in whales that use echolocation
- Despite reliance on medial and tail musculature for swimming, cerebellar anterior lobe, especially lobule I/II, is poorly developed



Paulin: Bats

- Microbats rely on echolocation
 - They are more agile in flight than birds, but unlike birds, have a relatively small cerebellum, except for enlarged vermal lobules VI-VIII
 - Enlarged region is analogous to enlargement seen in echolocating whales
- Macro bats (megabats) are fructivores (fruit-eating) and rely on vision for navigating
 - No expansion of vermal lobules VI-VIII
- Echolocating bats and whales differ vastly in their locomotion: bats on forelimbs and whales on axial musculature
 - yet cerebellar region of expansion is related to common auditory perception requirements rather than different motor requirements



Paulin: Cats

- Cerebellar cortex responsive to auditory stimuli
- Sensitive to direction of movement of stimuli
- 2/3 of auditory region neurons are sensitive to interaural time and intensity differences
- 1/3 have preference for acoustic targets moving along specific path



Paulin: Spider Monkeys

- Very agile
- Prehensile tail used as 5th hand
- Tail region in lobules I, II highly expanded
 - Has been interpreted as cerebellar expansion associated with a motor system
 - However, tail also has sensitive glabrous (hairless) skin on the underside tip of tail, used for sensory exploration



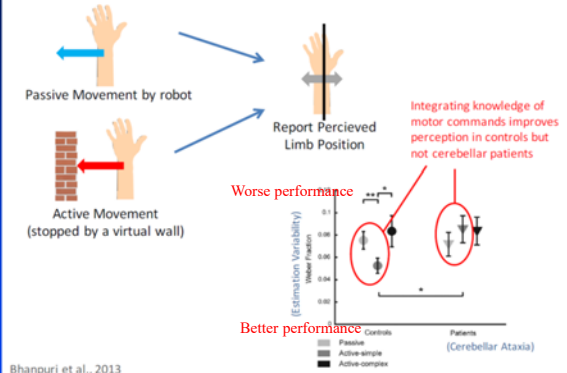
Paulin's Conclusion

- Cerebellum is more likely involved in tracking movements than making movements

Rebuttal to arguments that cerebellum is involved with movement

- Correlation between relative size and complexity of cerebellum and animal's agility
 - Motor complexity is correlated with other aspects of functional anatomy, including sensory systems and perceptual capabilities
- Particular lobules are expanded in relation to fine motor control systems in humans and other animals
 - However, these motor systems are also sensory systems used in active exploration. Also note cases where echolocation produces common cerebellar expansion in animals with different motor requirements
- Cerebellar damage or disease produces deficits in motor control and coordination, but not perceptual deficits
 - Perceptual deficits that cannot be attributed to motor deficits have been reported (e.g., inability to locate tactile stimulus). Refer also to Adrian Haith's lecture, which pointed out that proprioceptive deficits in cerebellar patients are more apparent during simple limb movement

Forward models improve proprioception



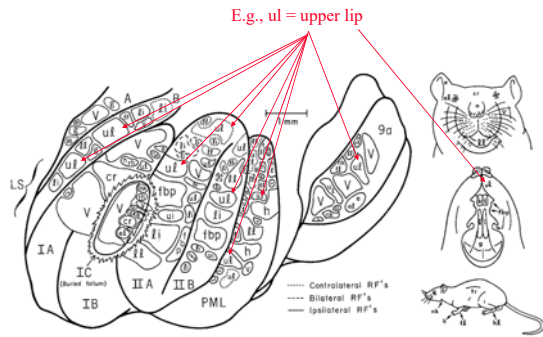
Rebuttal (cont.)

- Neuronal activity in cerebellum is related to movements
 - Sensory inputs are correlated with motor outputs
 - So does cerebellum control movements or analyze sensory data during movements?
 - Timing of cerebellar activity not informative:
 - Both info on intended movement and reafference would be useful for analyzing sensory data
- Cerebellar outputs go to known motor and premotor regions
 - Does not imply that cerebellar output is restricted to motor control
 - Rather, cerebellar computation may be useful for motor control
 - Bower goes 1 step further: Cerebellum projects to motor system to influence it so that it acquires better sensory data
 - Projections to other non-motor regions (like DLPFC) also suggests that cerebellar computation may be useful for non-motor behaviors

Bower: Control of Sensory Data Acquisition

- Electrophysiology in rat indicates a patch-like mosaic representation of different body parts
 - AKA: “fractured somatotopy”
 - Not random – the pattern is very similar in different rats

Rat Fractured Somatotopy

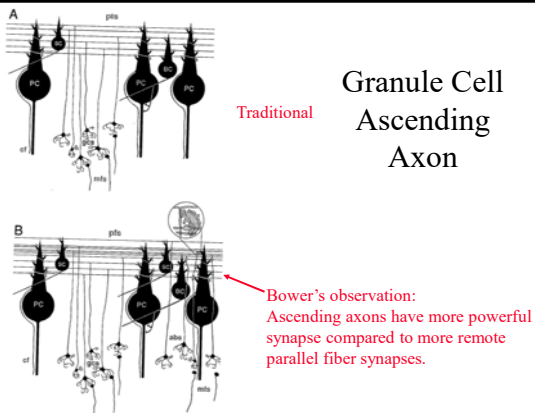


Bower, J.M. (1997) Int Rev Neurobiol 41, 489-513.

Physiological Observations

- Electrophysiological recordings showed that there is a strong vertical response of Purkinje cells to tactile stimulation
- A “beam” of responses derived from parallel fiber connections was not observed
- EM shows that the ascending synapses occur on a different region of the PC dendrite than do parallel fiber synapses
- Interpretation: Parallel fiber synapses have more of a modulatory role, providing a “context” for the more powerfully driven inputs

Granule Cell Ascending Axon

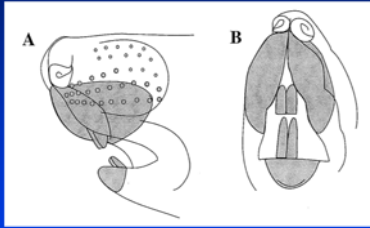


Bower, J.M. (1997) Int Rev Neurobiol 41, 489-513.

Interpretation

- The “dendritic state” of PCs reflects sensory information from many tactile surfaces distributed widely over cerebellar cortex
- This information modulates the ascending-branch mediated PC response to its specific input

Why Sensory vs Motor?



Bower, J.M. (1997) Int Rev Neurobiol 41, 489-513.

- Some surfaces are better represented than others
- Especially peri-oral surfaces that are in primary contact with objects during tactile exploration
- PCs from these regions fire during tactile exploration but not during chewing

Species-Specific Tactile Representation

- Cats and monkeys do not use perioral regions for tactile exploration
- Forelimbs are utilized
- Distal forelimb regions have large representation in cerebellum of cats and primates

What is the cerebellum controlling (Bower)

- Acquisition of sensory information
 - Exploratory touch requires active control of data being obtained from all the surfaces in contact with the object
- Cerebellum monitors incoming data from these surfaces and adjusts positions relative to each other and to object
 - Level of operation therefore temporally would be 10-100 ms, and spatially at the resolution of receptors 10s-100s of micrometers

Necessary Algorithm for Sensory Acquisition?

- One in which sensory input is interpreted in context of other sensory data from other receptors
- Fractured somatotopy and modulation from parallel fibers would achieve this

Role of cerebellar outputs?

- To influence motor centers that directly control the positions of tactile sensory surfaces
- E.g., microstimulation of cat cerebellar cortex caused withdrawal paw movements of areas of skin that corresponded with skin receptive field

Implications of this Hypothesis

- Cerebellum should receive high quality sensory data from structures related to movement
 - Spinocerebellar proprioceptive and tactile pathways are extensive and most rapidly conducting

Implications of this Hypothesis (cont)

- Motor coordination often recovers significantly after cerebellar damage
- This reflects other structures directly related to motor control to develop compensatory strategies for dealing with poor sensory data
- Most common clinical effect of cerebellar damage is general slowing down
 - A reflection of additional computational time needed to organize movement in the presence of badly coordinated sensory data

Implications of this Hypothesis (cont)

- Cerebellum receives input from all sensory systems, and cerebellar neuronal organization is invariant
- Thus, this theory of sensory acquisition should apply to all sensory systems

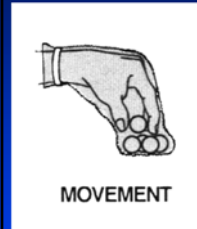
Gao et al. Experiment



- fMRI scanning in 6 healthy subjects (blindfolded)
- 4 tasks were performed during the scan
 - CS = Cutaneous Stimulation
 - Subjects passively received sandpaper rubbed against immobilized fingers of both hands
 - CD = Cutaneous Discrimination
 - Asked to actively compare (without responding) whether coarseness of sandpaper in 2 immobilized hands matched
 - Coarseness changed randomly every 3 sec
 - 4 grades of coarseness (60, 100, 150, 400)

Gao et al (1996) Science 272, 545-547.

Gao et al. Experiment (cont)



- Tasks (cont)
 - GO = Grasped Objects
 - Each hand enclosed in sock containing identical sets of 4 differently shaped stimuli
 - Wooden spheres with 1, 2, or 3 faceted surfaces
 - Pick them up, roll in fingers, then release
 - GOD = Grasped Objects Discrimination
 - Pick up object in 1 hand & feel shape while other hand feels another object – are they identical?
 - If different, drop object in right hand and find another
 - If identical drop both objects and start again
- Pre-scan training was designed to equate amount of movements for each task

Gao et al. Experiment (cont)

	No Motor	Motor
No Discrim	CS	GO
Discrim	CD	GOD

Sensory Acquisition Hypothesized order of activation

GOD > CD > CS > GO

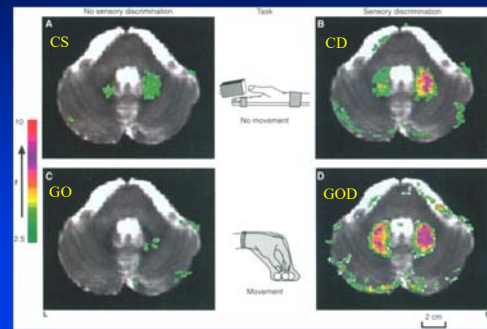
Motor cerebellar hypothesis:

(GOD = GO) > (CS = CD)

Gao et al. Experiment (cont)

- One axial slice (6 mm) through dentate nucleus was chosen
 - Estimate: >60% of total dentate volume is in slice
- Block Design (156 sec blocks)
- Task alternating with rest was used to calculate regressors for analysis

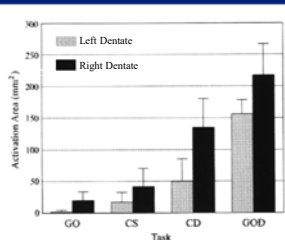
Results



Gao et al. (1996) Science 272, 545-547.

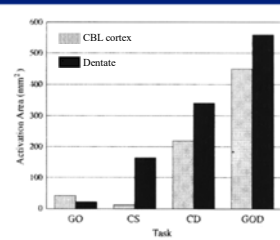
Results

Dentate Nucleus



Gao et al. (1996) Science 272, 545-547.

Dentate & CBL Cortex (bilat)



Parsons et al. (1997) Learn Mem 4, 49-62.

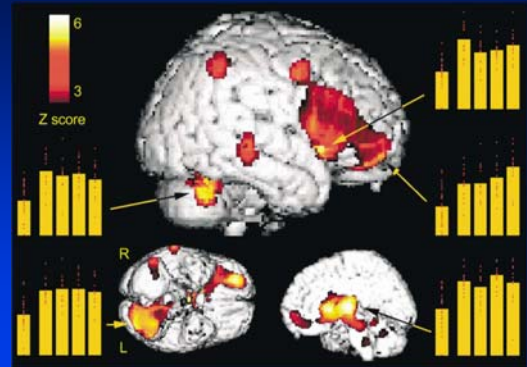
Results seem inconsistent with a purely motor cerebellar hypothesis

What about other sensory modalities?

Belin et al 2002

- Auditory duration discrimination task
- Task: Is test sound longer than a standard sound of 300 ms duration?
- Scanned while passively listening to standard sound, and while discriminating changes in sound duration

Duration Discrimination vs Passive Listening to Standard



Belin et al. (2002) Neuropsychologia 40, 1956-64.

Is Duration a Factor?

- Timing is another proposed function of the cerebellum
- However different auditory studies have investigated other features of auditory processing
 - Cerebellar activation still shows up

Cerebellum and Auditory Function Meta-Analysis

- Study inclusion criteria:
 1. Published in peer-reviewed journal
 2. Coordinates reported in standardized stereotaxic space
 3. Imaged volume had to include cerebellum as well as cerebrum
 4. Healthy normal subjects (without musical training)
 5. At least one low-level contrast without cognitive or emotional demands
 - Excluded human vocal sounds, machinery, environmental sounds, music or musical instruments
 6. Had to exclude motor tasks, e.g., button presses, finger lifting, or had to control for them in the contrast
- 17 articles met criteria, 2 removed because of identical research group

Final Selection

- 15 articles
- 27 selected contrasts containing a variety of passive and active auditory tasks using synthesized stimuli
- Total of 231 activation foci

TABLE 1. Summary of studies included in the meta-analysis

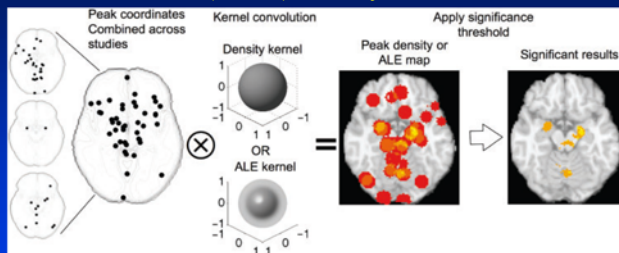
Article and contrast	Imaging modality	n	Filter (mm)	Stimuli	Stimuli presentation	Foci
Passive listening						
Aichermann et al., 2001 "Main effect"	fMRI	8	10	Clicks	Monaural	4
"Secondary effect"						2
"Tertiary effect"						2
Griffiths and Casen, 1995 "Diffusion effect"	fPET	4	16	Broadband noise	Monaural	3
Griffiths et al., 2000 "Conditioned speech vs. noise"	fPET	4	8	Pure tones	Monaural	4
"Blending vs. ordinary"	fPET	12	10	Pure tones	Monaural R	22
Lockwood et al., 1998 "1/3 kHz, 70 dB HL vs. noise"	fPET	9	10	Clicks	Monaural	15
"1/3 kHz, 70 dB HL vs. noise"	fPET	9	10	Clicks	Monaural R	3
Chiodini et al., 2002 "Main effect listening"	fPET	9	10	Clicks	Monaural	9
Finer et al., 2002 "All responses vs. rest"	fPET	9	10	Clicks	Monaural R	3
"Listening vs. rest"	fPET	9	10	Clicks	Monaural R	3
Kan et al., 2007 "Listening vs. rest"	fMRI	13	8	Pure tones	Monaural	2
Rosen et al., 1994 "Pure tones vs. rest"	fPET	9	11 x 12 x 14	AM tones, pure tones	Monaural R	3
"All FM AM vs. rest"	fPET	9	11 x 12 x 14	AM tones, pure tones	Monaural R	4
"All FM AM vs. pure tone"	fPET	9	11 x 12 x 14	AM tones, pure tones	Monaural R	2
Neundorfer et al., 2002 "Speech demand vs. ignore stimulus"	fPET	18	10	Pure tones	Monaural R/L	16
Thivard et al., 2001 "Secondary vs. rest"	fPET	8	15	Complex sounds	Monaural	4
"IM vs. rest"	fPET	8	15	Complex sounds	Monaural	4
"IM vs. ordinary"	fPET	8	15	Complex sounds	Monaural	4
Active listening						
Bills et al., 2006 "Intensity discrimination vs. standard sounds"	fPET	7	12	Complex tones	Monaural	4
Bills et al., 2002 "Duration discrimination vs. standard sounds"	fPET	7	12	Complex tones	Monaural	4
Preuss et al., 2004 "FM complex vs. rest"	fPET	10	15 x 15 x 9	FM pure tones	Free field	19
"vs. FM and Berlin, 2003"	fMRI	8	8	Four pulses, noise bursts	Monaural R	34
"Hemispheric matching vs. rest"	fMRI	8	8	Four pulses, noise bursts	Monaural R	13
"Backward matching vs. rest"	fMRI	8	8	Four pulses, noise bursts	Monaural R	4
"Backward vs. simultaneous"	fMRI	8	8	Four pulses, noise bursts	Monaural R	5
Vannestenen et al., 2001 "Complex songbirds vs. single tones"	fMRI	15	8	Complex sounds, pure tones	Monaural	5
Total						231

*Contrasts containing contralateral activations in indicated study.
AM, amplitude modulated; FM, frequency modulated; HL, hearing level; IM, spectral motion.

Studies Selected

Petacchi et al. (2005) Hum Brain Mapp 25, 118-28.

Activation Likelihood Estimate (ALE) Analysis



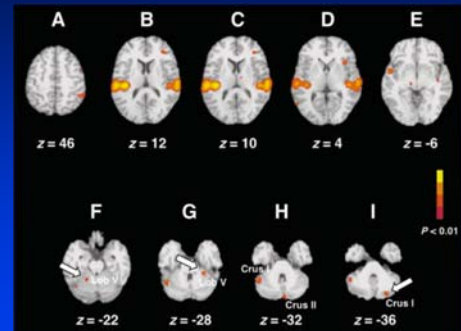
Collect reported foci coordinates from various studies

Smooth those foci. Then for each voxel count the number of overlapping foci, n . Is n larger than what would be expected by chance?

Randomly distribute the foci in the brain 1000s of times, forming a probability distribution of the number of overlapping foci.

Wager et al. (2007) Soc Cogn Affect Neurosci 2, 150-8.

Results



Petacchi et al. (2005) Hum Brain Mapp 25, 118-28.

Coordinates of Significant ALE Maxima

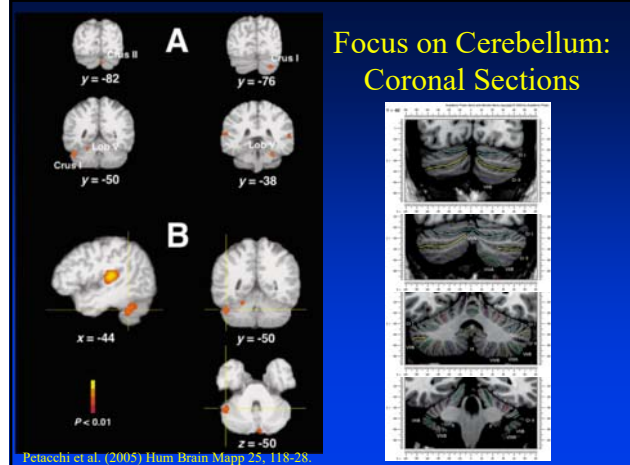
TABLE II. Locations of significant ALE maxima

Region	BA	Coordinates			Volume (mm ³)	ALE ($\times 10^{-3}$) ^a
		x	y	z		
Auditory cortex						
Left transverse temporal gyrus	41	-40	-26	10	11032	27.20
Right superior temporal gyrus	42	60	-20	10	9608	20.32
Left superior temporal gyrus	22	-50	2	-6	768	11.66
Cerebellum						
Left cerebellum, crus I		-44	-50	-32	1048	10.33
Right cerebellum, lobule V		28	-38	-28	336	10.26
Right cerebellum, crus I		26	-76	-36	312	10.00
Left cerebellum, lobule V		-20	-50	-22	184	8.99
Right cerebellum, crus II		4	-82	-32	152	7.88
Right hemisphere						
Right middle frontal gyrus	10	34	38	12	416	10.00
Right anterior insula	36	18	4	4	1024	9.89
Right inferior parietal lobule	40	48	-46	46	528	9.72

Nomenclature of cerebral areas and corresponding Brodmann areas (BA) is based on Talairach and Tournoux [1988]. Cerebellar regions are designated according to Schmahmann et al. [2000].
^a $P < 0.01$, corresponding ALE threshold value = 6.00×10^{-3} .

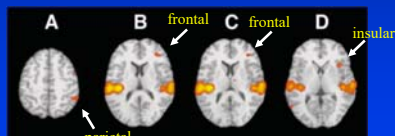
Petacchi et al. (2005) Hum Brain Mapp 25, 118-28.

Focus on Cerebellum: Coronal Sections



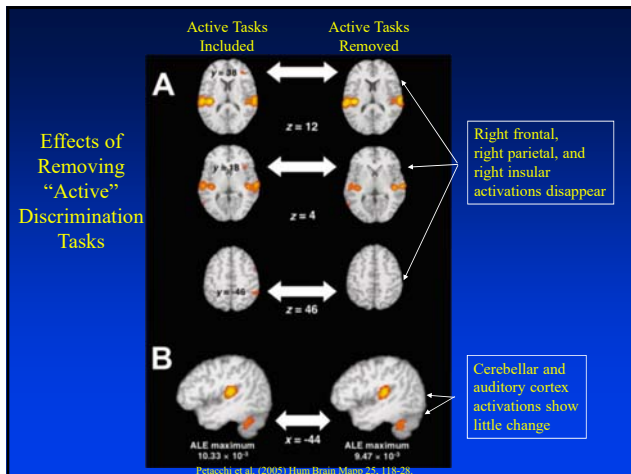
Role of Attention?

- Could the cerebellar activations reflect attentional demands of the tasks?
- Right parietal, right frontal and right insular regions have been linked in other studies with attention



Removal of Active Tasks

- To test attentional contribution, 5 studies requiring discrimination of stimuli were removed
- This resulted in disappearance of right frontal, parietal and insular regions but had little effect on cerebellar activations



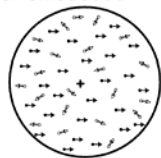
Baumann & Mattingley 2010

- Looked at both auditory and visual sensory acquisition
- Used a task requiring subjects to discriminate direction of a visual or auditory motion signal in noise
- Inspired by previous study of cerebellar patients (Thier et al, 1999), who were impaired at extracting a coherent visual motion signal embedded in noise

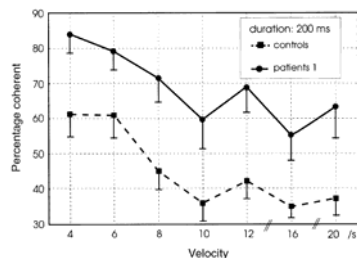
Cerebellar Damage Impairs Ability to Detect Coherent Motion

Thier et al. (1999) Brain 122 (Pt 11), 2133-46.

direction of coherent motion embedded in noise



This is percentage of dots that were coherent at subjects' threshold for detecting coherent motion. Thus, cbl patients needed more dots to be moving coherently in order to detect coherent motion. This was constant over different dot velocities.



Baumann & Mattingley 2010 (cont)

- During fMRI, subjects received auditory or visual trials that had either
 - No coherent motion (No Signal)
 - Difficult to detect coherent motion (Low Signal)
 - Easy to detect coherent motion (High Signal)
- (Thus, 6 conditions total)
- Each trial consisted of 1 sec stimulus followed by 2 sec for response
- Blocks of 4 auditory or 4 visual stimuli
 - Subjects cued for aud/vis at the beginning of block

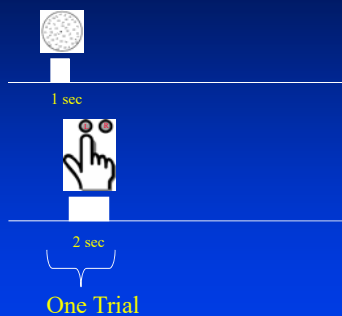
Baumann & Mattingley 2010 (cont)

- Subjects instructed to push one of two buttons to indicate if coherent motion went to the left or right
 - Subjects unaware of no motion condition
 - Told that some trials would be below threshold and that they should make best guess

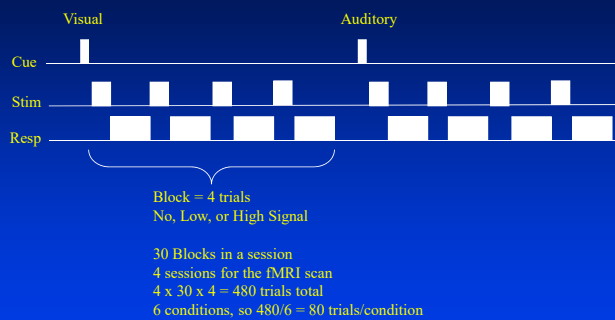
Baumann & Mattingley 2010 (cont)

- Subjects got 30 blocks (120 trials) / session
 - At least 2 training sessions before fMRI
 - Eye movement recording: subjects maintained cross fixation
- For fMRI, 4 scanning sessions, thus 480 trials total
 - 80 trials for each of the 6 conditions
 - Each block separated by 0-6.75 sec rest

Reviewing...



Blocks



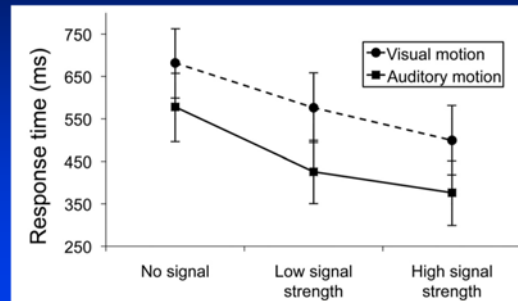
Behavioral Results: Accuracy

- High and low signal conditions for both auditory and visual had >89% accuracy
- However, significant main effects of signal strength and modality, no interaction
 - Auditory > Visual in accuracy
 - High Signal > Low Signal

Baumann and Mattingley (2010) J Neurosci 30, 4489-95.

Behavioral Results: RT

Significant main effects of signal strength and modality, no interaction



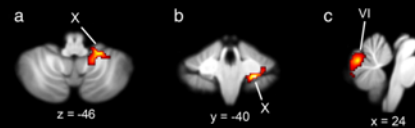
Baumann and Mattingley (2010) J Neurosci 30, 4489-95.

fMRI Results: Question 1

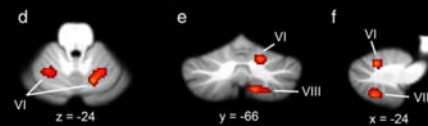
- Are there any regions in which visual performance of this task produces greater activation than auditory performance, and vice versa?

fMRI Results

Visual > Auditory (No, Low & High signal combined)



Auditory > Visual (No, Low & High signal combined)



0 3 6 9 12 t-value

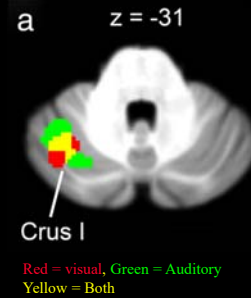
Baumann and Mattingley (2010) J Neurosci 30, 4489-95.

fMRI Results: Question 2

- Bower argues that cerebellar involvement is greater when finer level of sensory data acquisition is needed
- Thus, are increases in neural activity associated with decreases in signal strength of the motion stimuli?

- Regions of Crus I showing a negative correlation between brain activation and signal strength, i.e., greater activation when signal is low, which is consistent with sensory acquisition role of cerebellum
- Overlap suggests that this region may be supramodal

fMRI Results



Baumann and Mattingley (2010) J Neurosci 30, 4489-95.

Conclusions

- fMRI results are consistent with sensory acquisition hypothesis of Bower
- Also consistent with Paulin's view that cerebellum is involved with tracking movements