Chris Miall

Internal models in the cerebellum: coordination, learning and state estimation

Behavioural Brain Sciences
School of Psychology
University of Birmingham

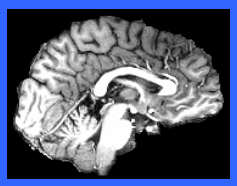
fMRI
Hiroshi Imamizu
Ned Jenkinson

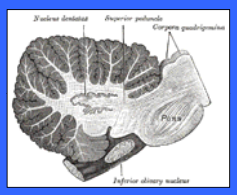
Electrophysiology
Xuguang Liu
Edwin Roberson

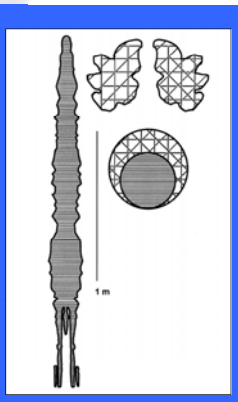
TMS
Lars Christensen
James Stanley
Owen Cain
Dominic King

funding
The Wellcome Trust

Cerebellum – a huge neural resource



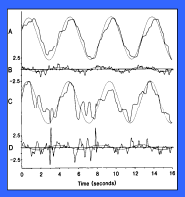




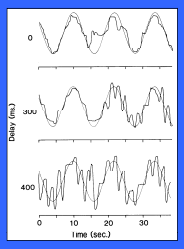
- maybe 30% of the total brain area
- greater than 50% of the total neuronal count
- highly conserved architecture
- expansion in primate in parallel with neocortex

Problems for control...

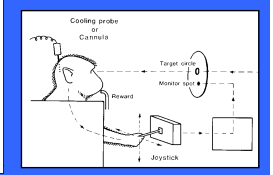
Cerebellar inactivation

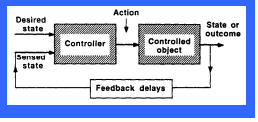


Delayed visual feedback



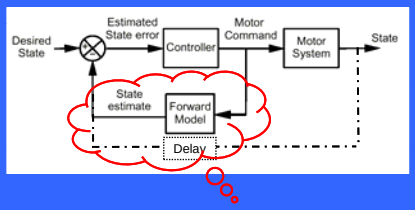
- temporal delays on sensory feedback
- hidden true state of motor system





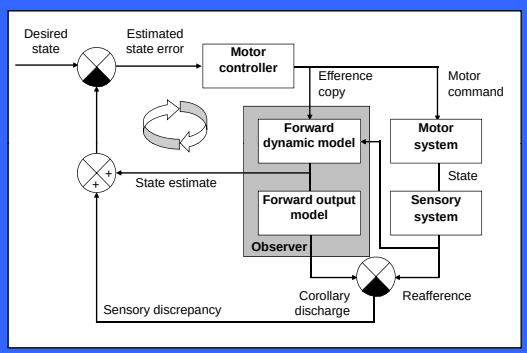
Miall, et al. (1986) *Exp. Brain Res.*
Miall, et al. (1985) *Neurosci.*

State Estimation & Feedback control



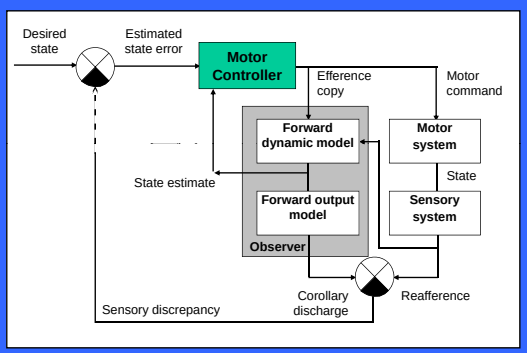
Cerebellar function?

1. Smith Predictor control



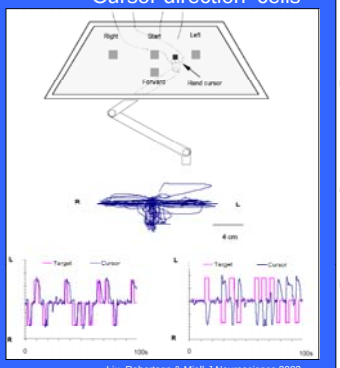
Miall, et al. (1993) *J. Motor Behaviour*

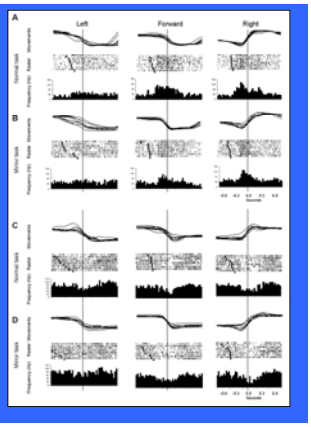
2. Smith Predictor control



Searching for a forward model

‘Cursor direction’ cells



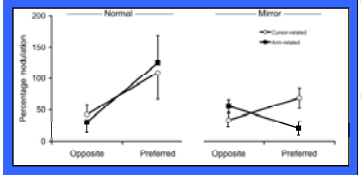


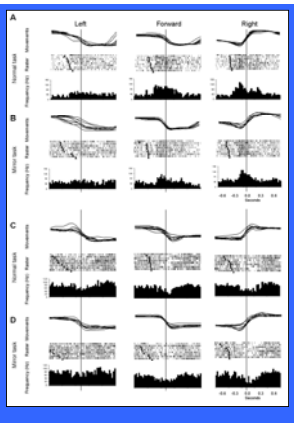
Liu, Robertson & Miall *J Neuroscience* 2003

Searching for a forward model

‘Cursor direction’ cells

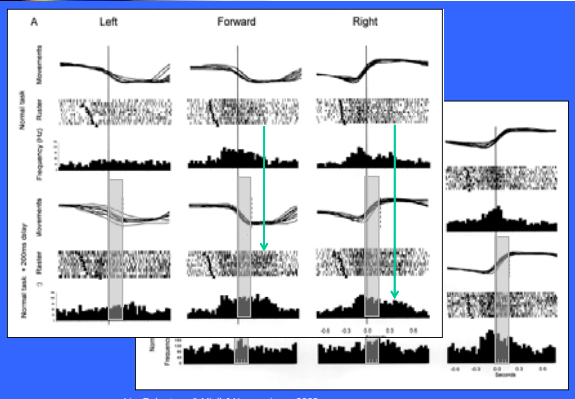
Task related neurones 173 (100%)			
Direction dependent neurons 59 (34 %)			Direction independent neurons
Cursor related	Arm related	Unclear	
30 (51%)	9 (15%)	20 (34%)	114 (66%)





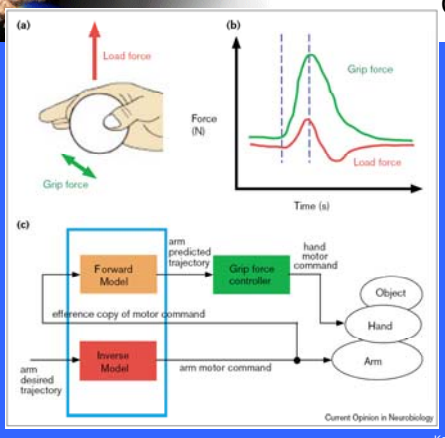
Liu, Robertson & Miall *J Neuroscience* 2003

‘Cursor’ cells with delay



Liu, Robertson & Miall *J Neuroscience* 2003

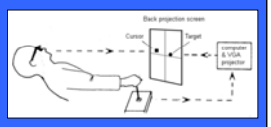
Coordination

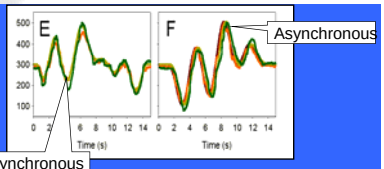


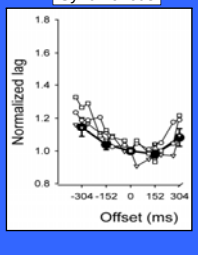
Coordination depends on predictive forward model

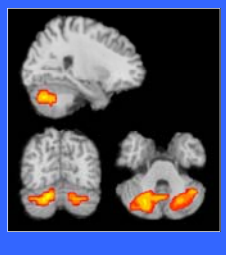
Kawato *Curr Opin Neurobiol.* (1999)

Cerebellar activation in eye-hand coordination



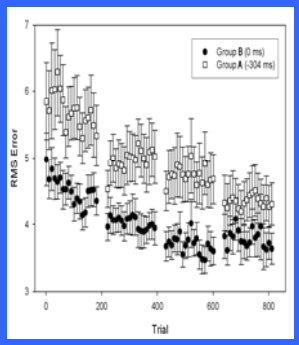


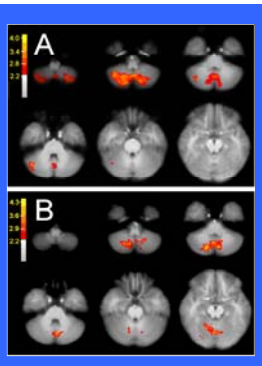




Miall Imamizu & Reckess *Nature Neuroscience*, 2001

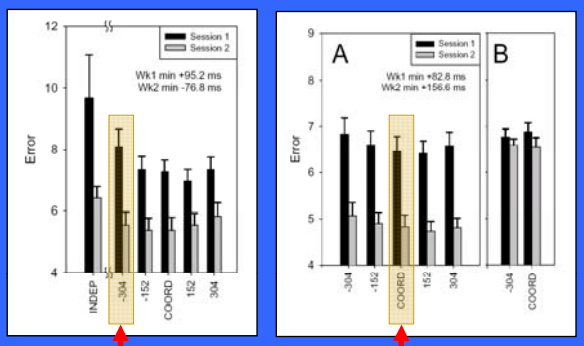
Learning related changes in performance and activation





Miall & Jenkinson *Exp Brain Res* 2005

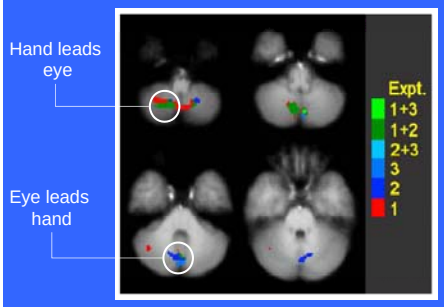
Performance changes with training

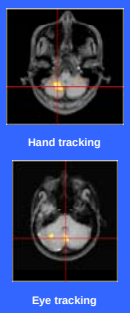


Training condition

Miall & Jenkinson, *Exp Brain Res*, 2005

Modularity in activation areas



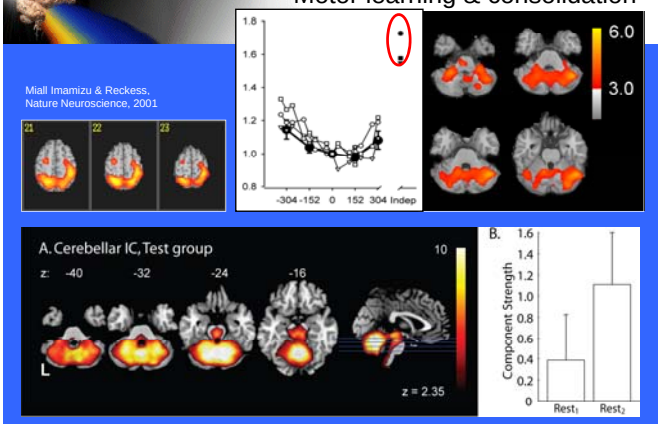


Miall & Jenkinson, *Exp Brain Res*, 2005

Miall, Imamizu, Miyauchi, *Exp Brain Res*, 2000

Motor learning & consolidation

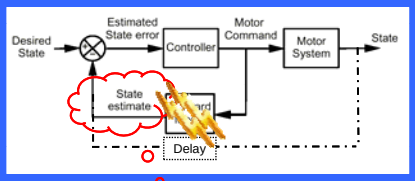
Miall Imamizu & Reckess, Nature Neuroscience, 2001



Albert, Robinson & Miall, *Curr Biol* 2009

Resting involvement in motor memory

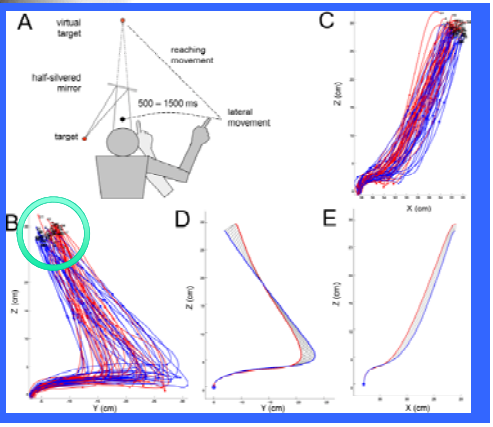
State Estimation & Feedback control



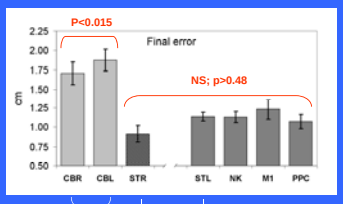
Cerebellar disruption

TMS & disruption of state estimation

Miall, Christensen, Cain & Stanley *PLoS Biology 2007*



Increase in terminal error



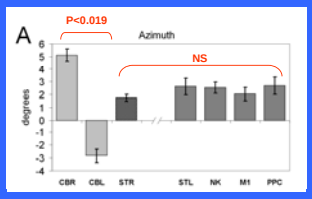
Pointing accuracy

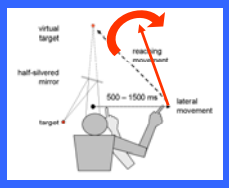
Errors increased
F(4,66) = 4.54,p=0.003

NK: Neck
M1: Motor cortex
PPC: SPL (p3 EEG position)

Startle
Cerebellum static
Cerebellum R/L

Directional error after TMS





Azimuth angle

ANOVA:
$F_{(4,61)} = 4.73$
$p = 0.002$

CBR/L Cerebellum
STR Cerebellum static
STL Startle
NK Neck
M1 Motor cortex
PPC Superior Parietal

Summary – motor control

1. TMS causes pointing errors consistent with planning from a previous hand position
2. "State estimation" interval is ~ 130 - 140 ms
3. Eye-hand coordination modulates cerebellar BOLD signal
4. Activation pattern suggests a modular arrangement, based on determinant or causal effector system
5. The causal relations and BOLD changes are experience dependent
6. Cerebellar neurons encode sensory predictive signals
7. Cerebellum provides a "forward" prediction of action

ABiALS themed questions

1. Anticipatory Behavior in Adaptive Learning Systems
   1. how do distributed spatial representations develop and how are they adapted?

      What are the cerebellar representations – Visual? Proprioceptive? Multimodal? Seem to be "exteroceptive"
   2. how can these (interacting) representations be effectively utilized to interact with the environment?

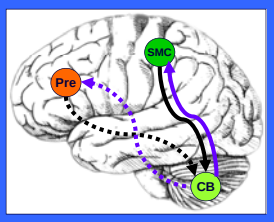
      Easy! Extension of predictions of "self" to predictions of effects within the environment
   3. how are more complex behavioral routines, such as object manipulations, tool usage, or joint actions, learned, represented in compressed form, and flexibly activated in interaction with the various sensorimotor spatial representations available?

      Cerebellar role(s) in cognition ...

Cerebello-cerebral connections

- Is there just one cerebellar process?
- Prediction and state estimation
- ...for motor function
- ...for cognitive processes

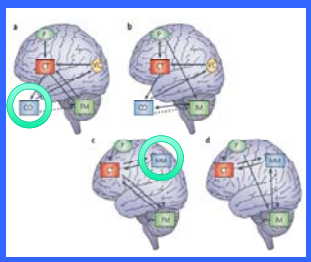
via strong connections with prefrontal cortical areas



Cortico-cerebellar interactions

a) Forward Model (FM) prediction of external controlled object

b) FM prediction of internal mental module



Ito M. (2008) Control of mental activities by internal models in the cerebellum. *Nat Rev.Neurosci* 9 (4):304-313.

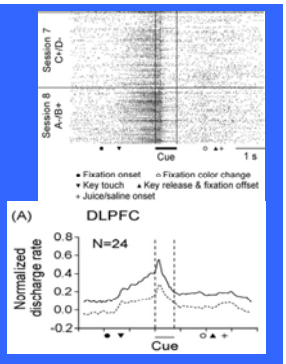
Cortico-cerebellar interactions

Prefrontal signals are preparatory and predictable, context (rule) dependent, coordinative (cueing stimulus processing)

Richard Ivry: Cerebellar patients have difficulties with sensory prediction, timing, language, memory, response preparation – but not categorical distinctions, odd ball detection etc

What aspects of cognitive function would be most sensitive to loss of "cerebellar function"?

Language – predictive processing



Yamada et al. (2010) *Neurosci Res* 67 162-171