A unified neurobiological model of time perception

Sundeep Teki
Auditory Group
Wellcome Trust Centre for Neuroimaging
University College London

Timing substrates

SENSORY CORTEX

HIPPOCAMPUS

PREFRONTAL CORTEX

SMA/PRE-SMA

BASAL GANGLIA

CEREBELLUM

Timing Mechanisms

- **Sub-second** vs. **Supra-second timing**

- **Event-based timing** vs. **Emergent timing**

Ivry et al.

- **Implicit** vs. **Explicit timing**

Coull et al.

- **Automatic** vs. **Cognitive timing**

Lewis and Miall

- **Duration-based (ΔT_i)** vs. **Beat-based timing (ΔT_i / T_{beat})**

Griffiths et al.

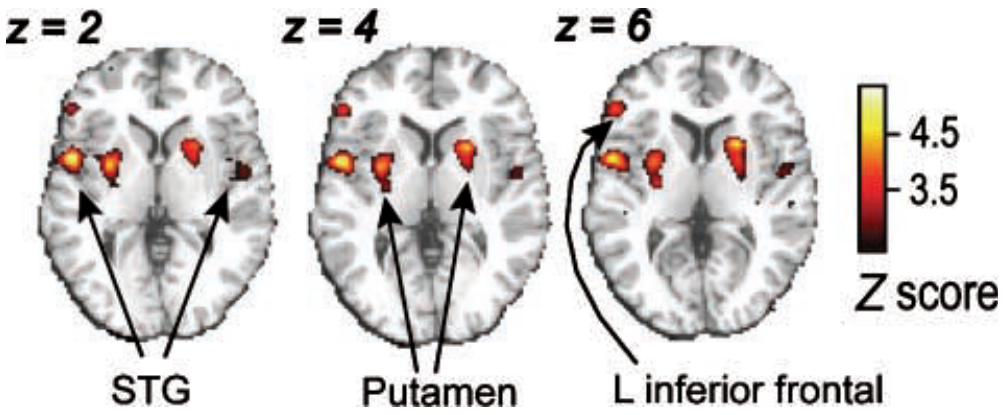
Beat-based timing

A regular beat offers beneficial temporal cues in perceptual timing

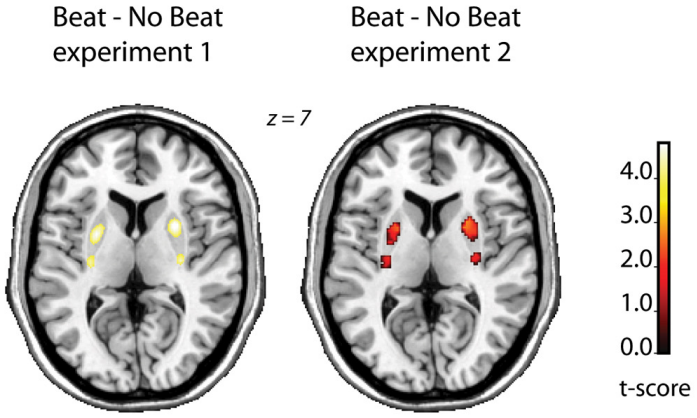
(Povel & Essen, 1985)

Parkinson's patients show deficits in perceptual timing tasks.

(Artieda et al. 1992, Harrington et al. 1998, Grahn & Brett, 2009)



Grahn and Brett, 2007



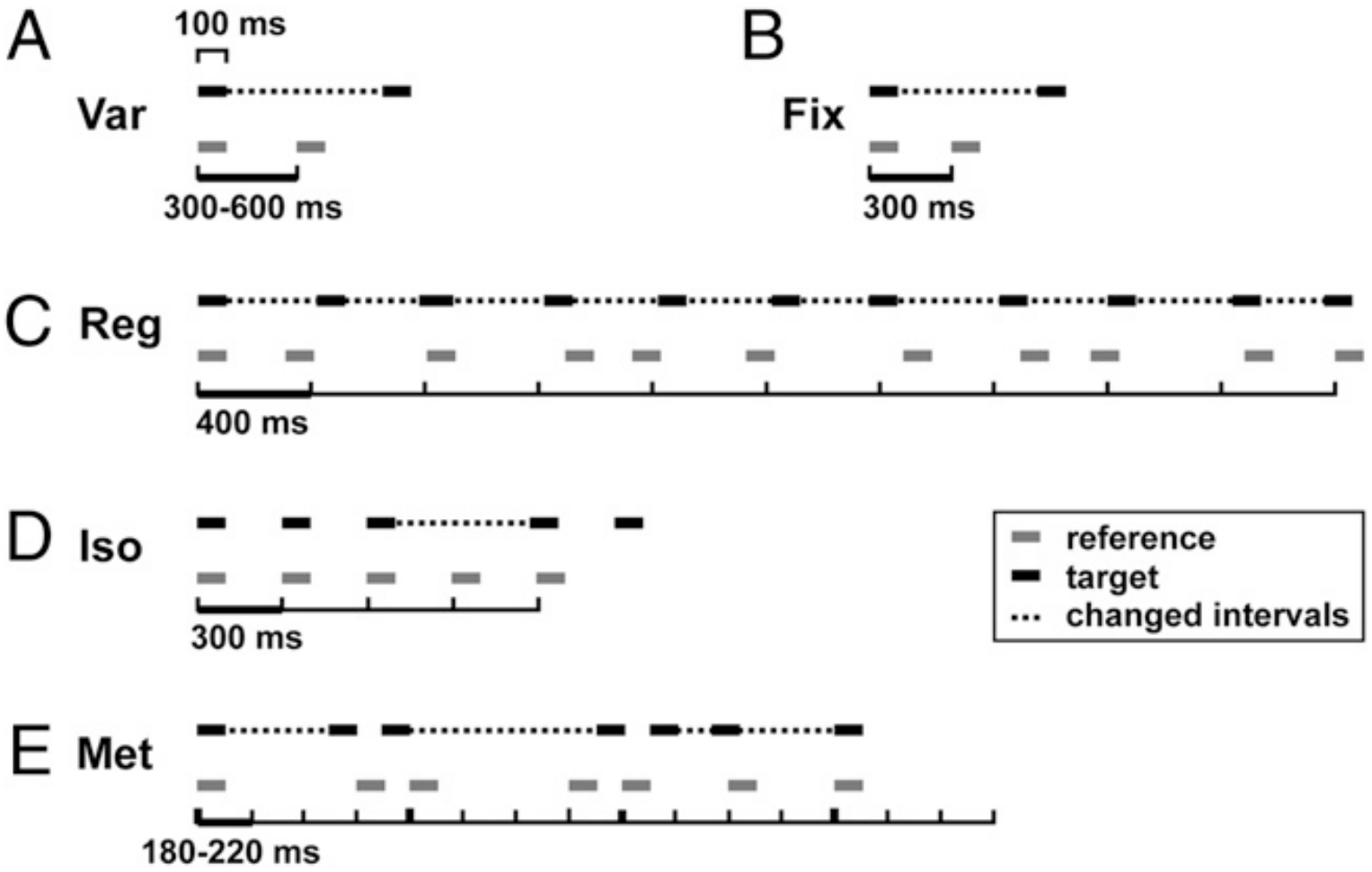
Grahn and Rowe, 2009

Basal ganglia, pre-SMA/SMA, and pre-motor cortex

implicated in perception of beat-based and metrical rhythmic sequences.

Duration-based timing

Patients with Spino Cerebellar Ataxia type 6:



(Grube et al., 2010. PNAS)

Rhythm & Timing

Aim: Test for dissociation between the timing functions of cerebellum and basal ganglia according to the rhythmic context of time intervals.

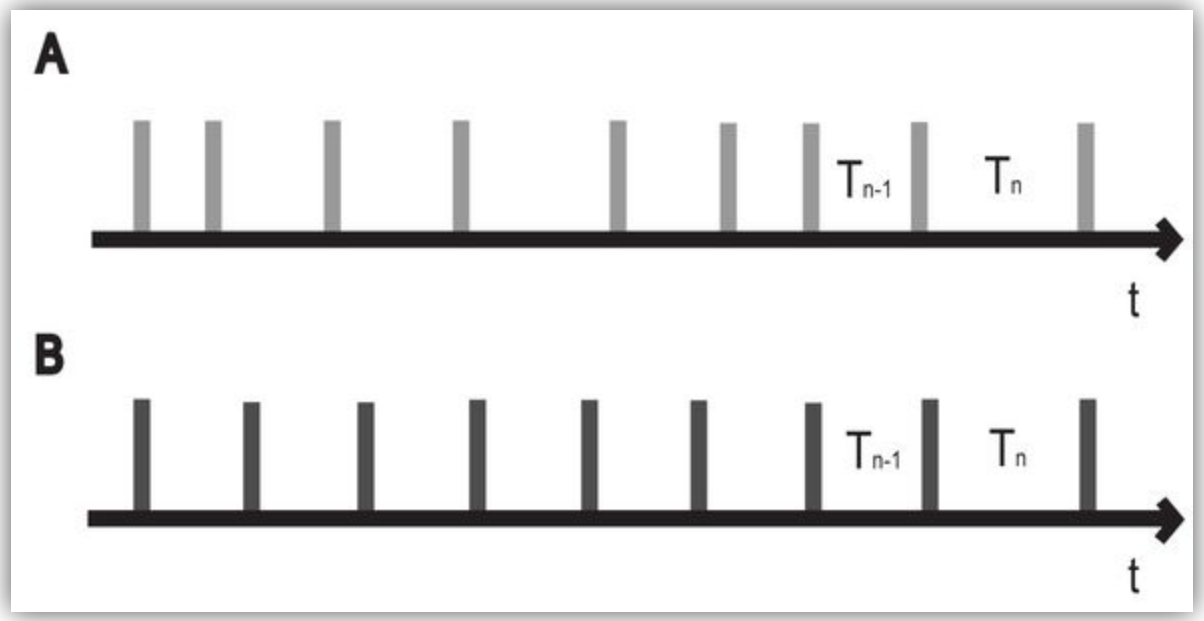
Hypotheses:

H1: Beat-based timing more accurate than duration-based timing

H2: Cerebellum more involved in absolute, duration-based timing

H3: Basal ganglia more involved in relative, beat-based timing

Stimulus and Task

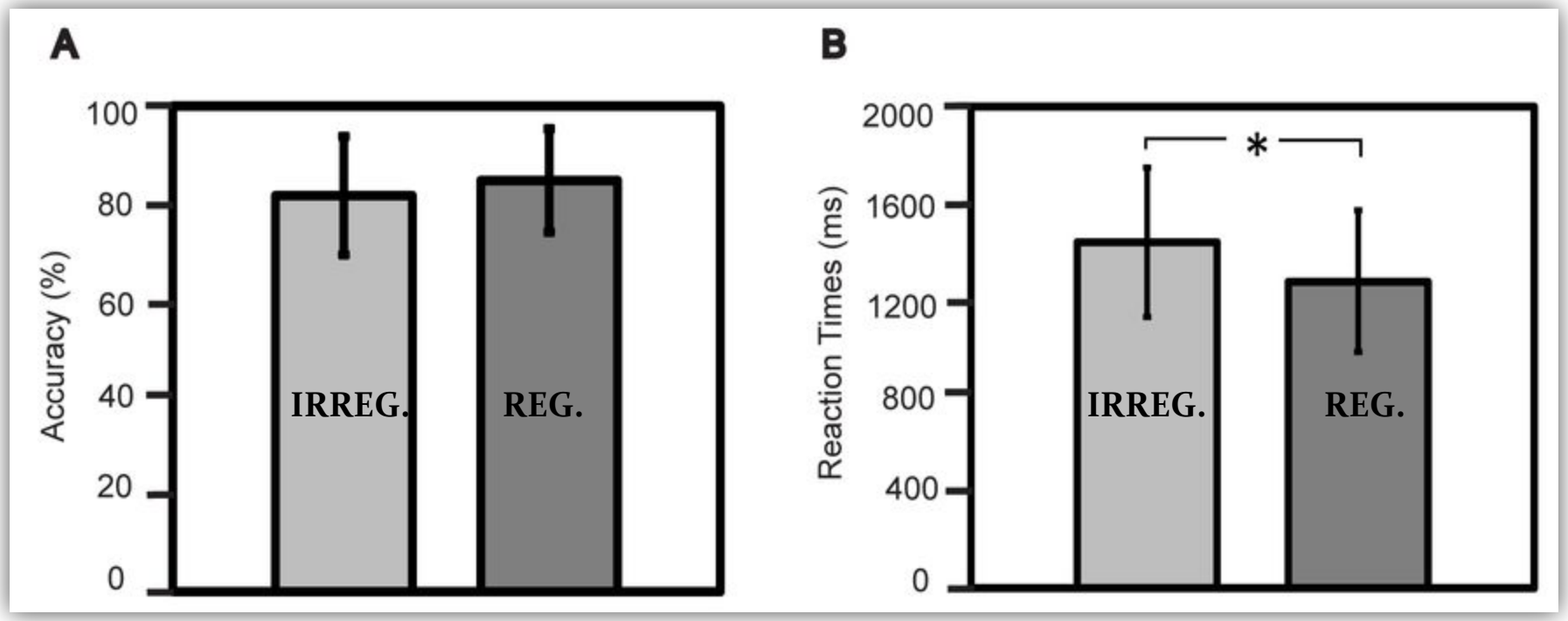


- ***Judge the duration of the final compared to the penultimate interval***
  T_n > / < T_{n-1}

Sequence A: Irregular with 15% average jitter

Sequence B: Regular with an isochronous beat

Behaviour in scanner



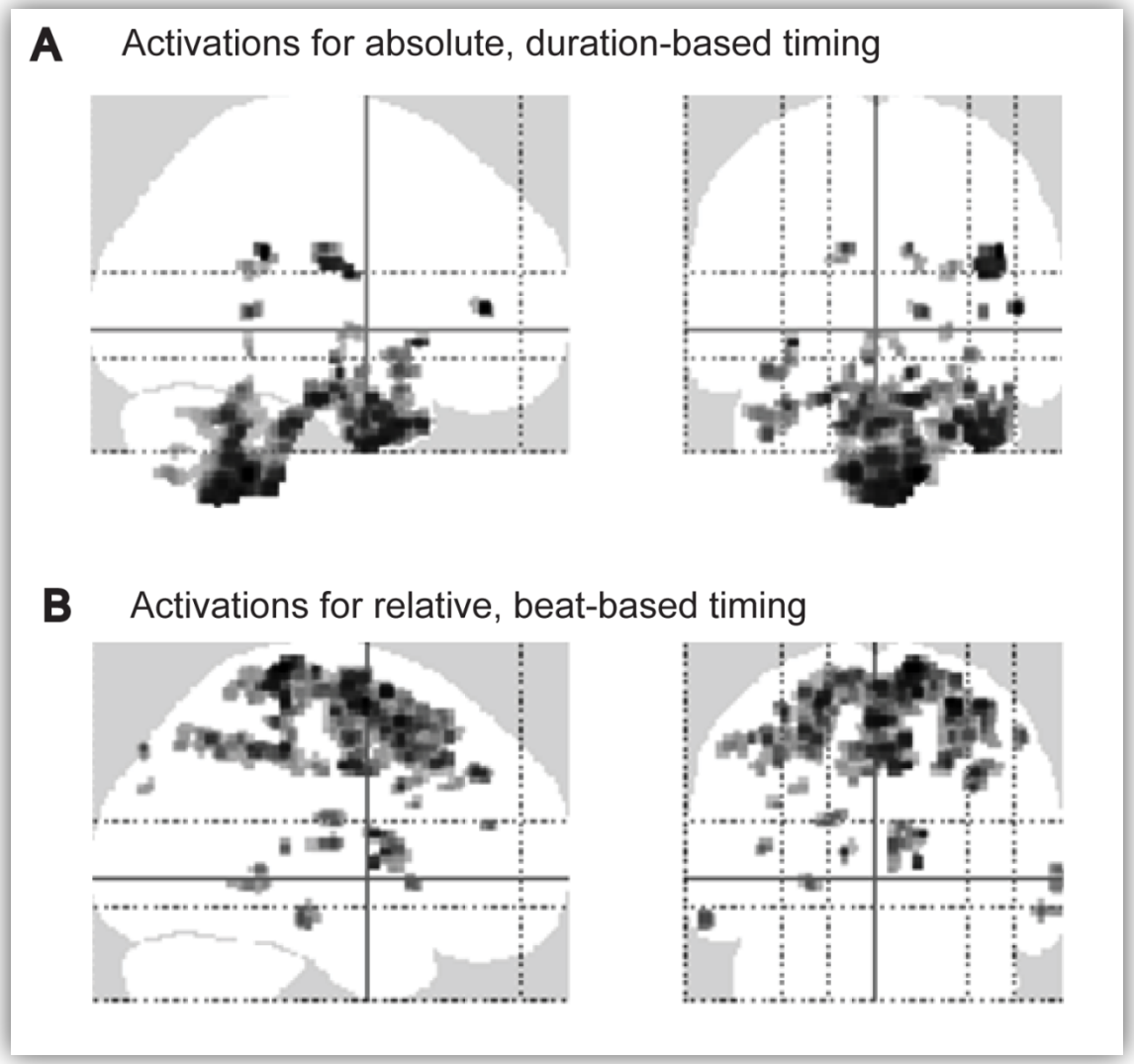
81.53% ± 12.28%

84.72% ±10.64%

1438 ± 297 ms

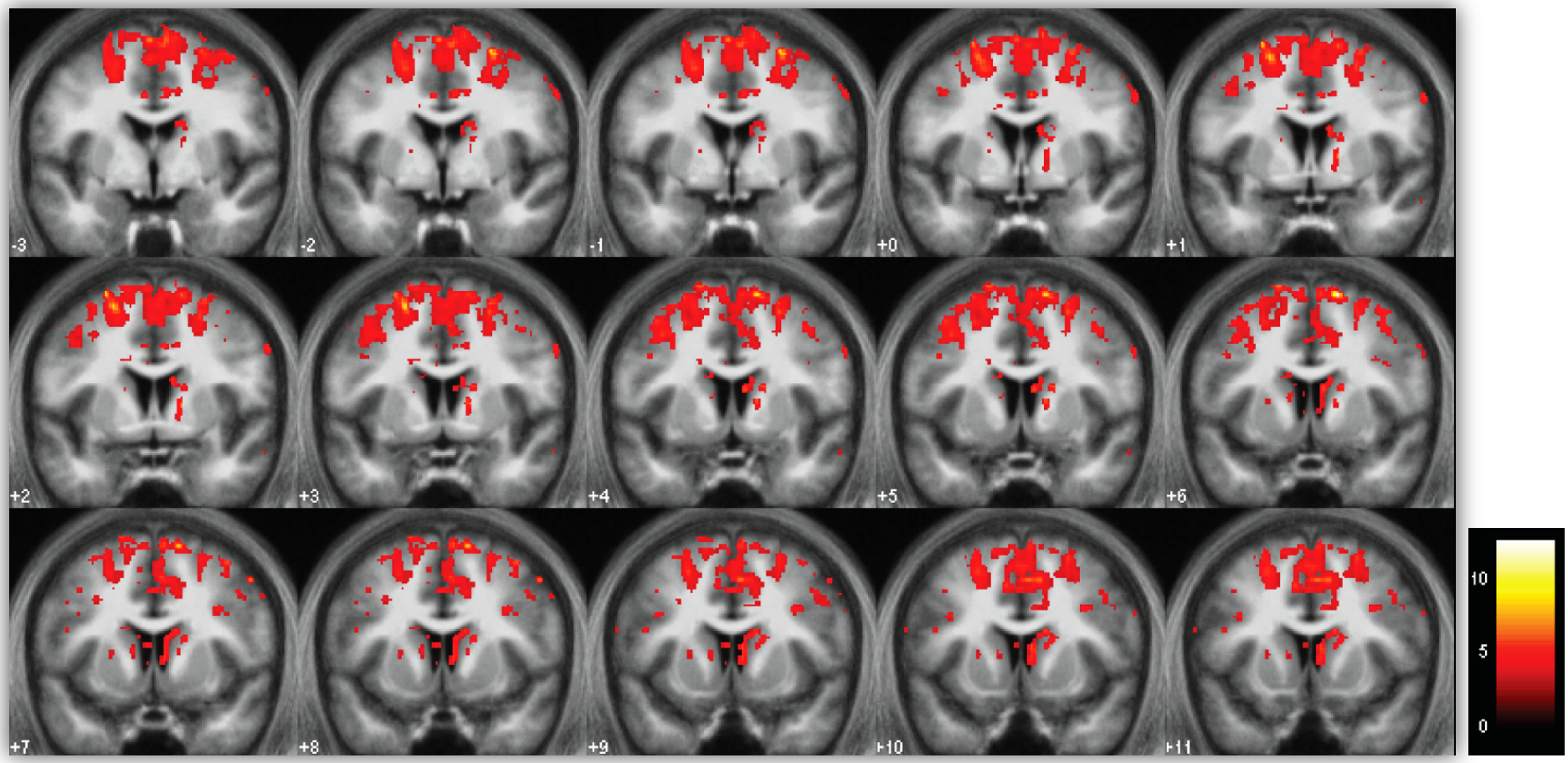
1275 ± 312 ms

fMRI Results



MNI space; t-value > 4.00 and extent threshold > 10 voxels

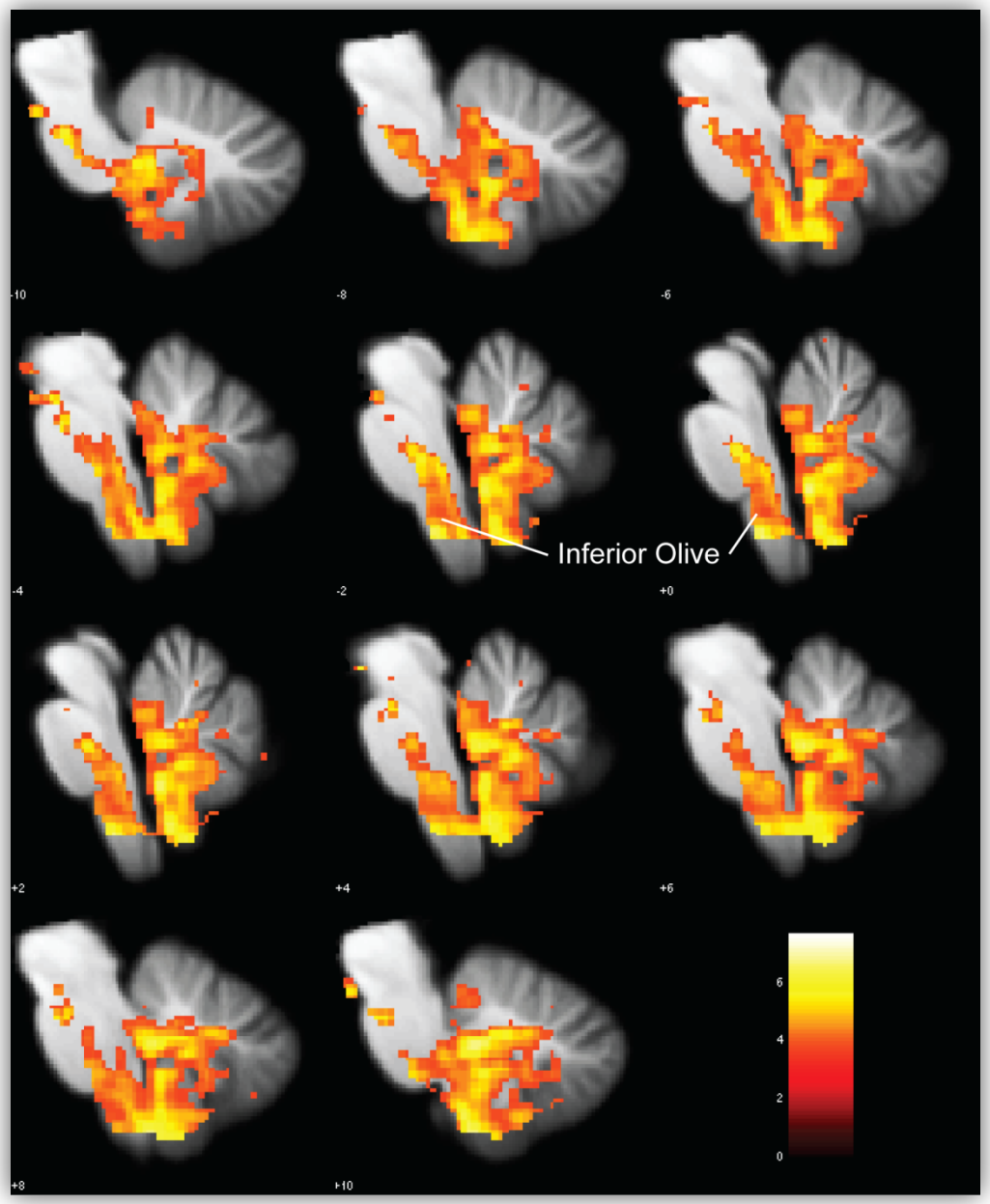
Striatal, premotor and prefrontal activations



x = -3 mm to + 11 mm

p < 0.001 (unc.)

Olivocerebellar activations

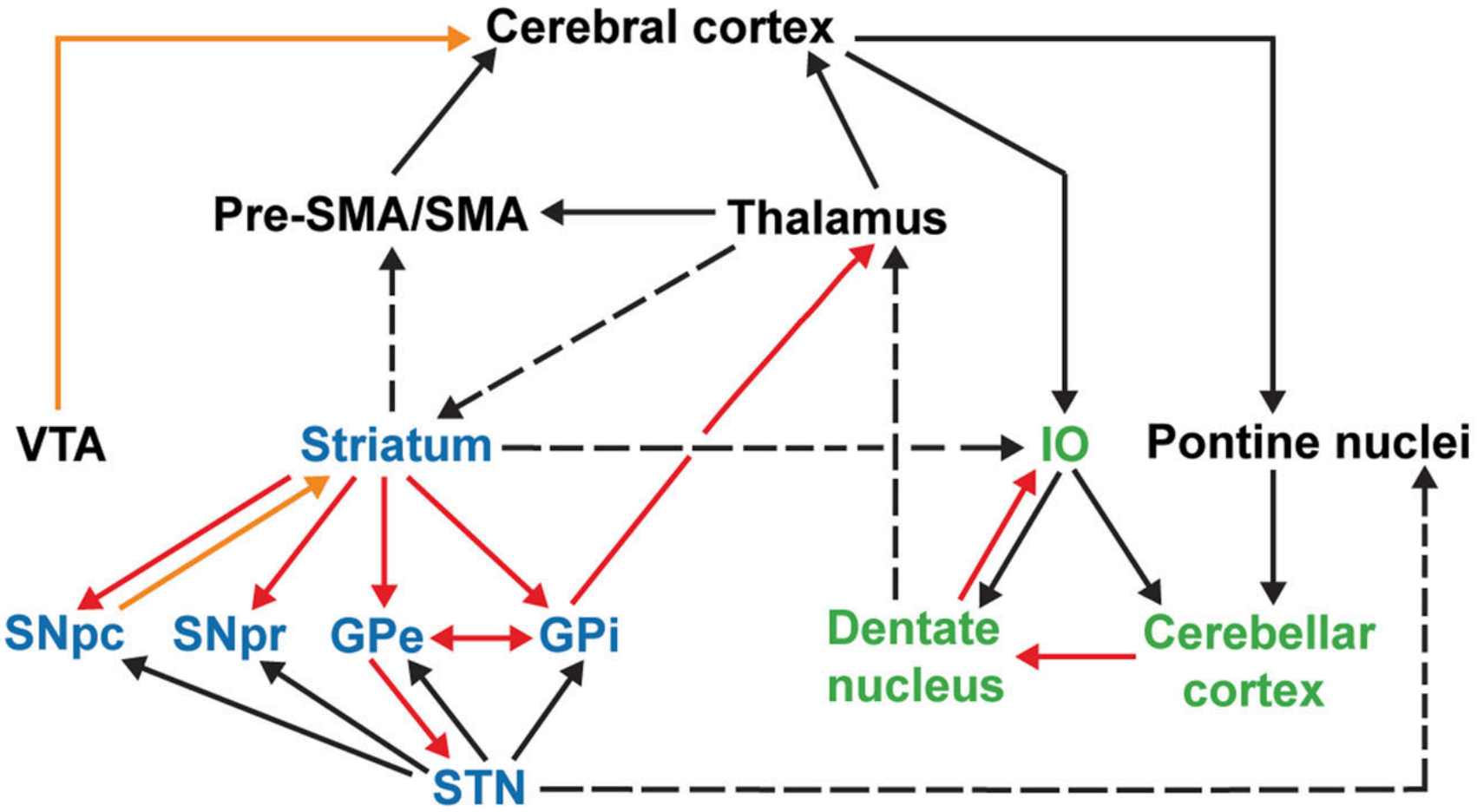


p < 0.001 (unc.)

x = -10 to +10 mm

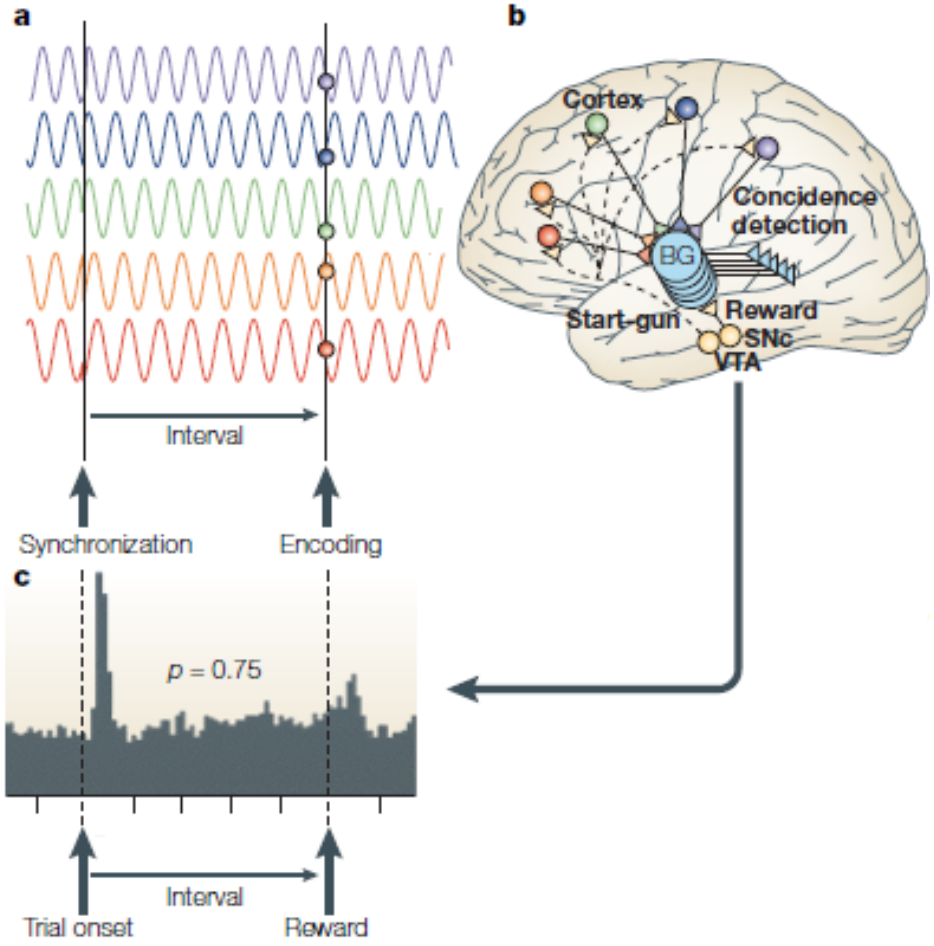
Teki et al., 2011
J Neurosci

Unified model



Teki et al., 2012
Front Int Neurosci

Striatal Beat Frequency Model



Matell and Meck, 2004; Meck, 2005; Allman and Meck, 2011

Unified model: Features

- Motor structures specialized for timekeeping in the brain
- Timing functions of BG and CB not necessarily independent
- BG network timing signal based on SBF model
- CB network timing signal based on known neurophysiology
- The two key networks interact to improve the accuracy of the timing signal

Assumptions:

- Striatum serves as default/central timekeeper
- Beat-based clock operates for timing stimuli in predictable, beat-based context
- Duration-based clock more active for stimuli in irregular, isolated context

Unified model: Anatomy

- BG network based on known anatomy (SBF model)
- CB network based on known anatomy

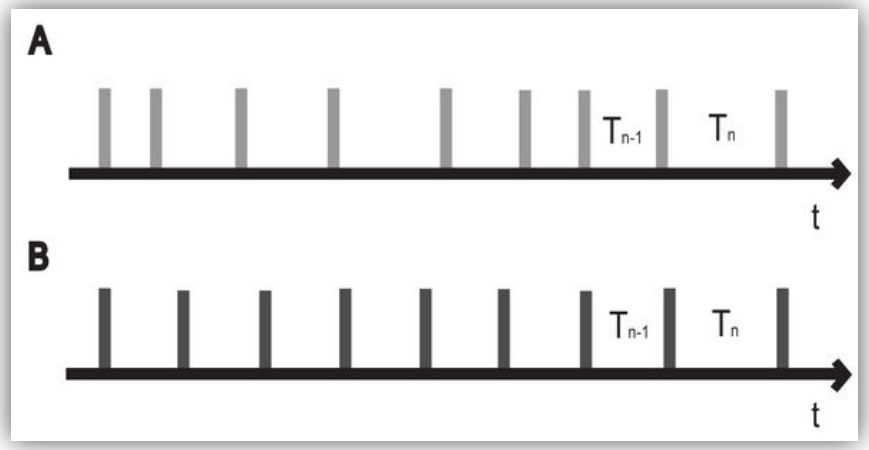
- **Novel connections:**

  Interconnections between striatal and cerebellar networks (c.f. Strick lab):

  - Dentate => Thalamus => Striatum
  - STN => Pontine nuclei => Cerebellar cortex

Unified model: Timing

- **Function**: beat-based timing with error-correction by duration-based clock



Regular context:
beat-based clock produces less errors in predicting next time intervals =>
less error-correction required and lesser contribution of CB clock

Irregular context:
beat-based clock produces larger errors in predicting next time intervals =>
greater error-correction required and greater contribution by CB clock

Empirical support

Is there a strict functional dissociation?

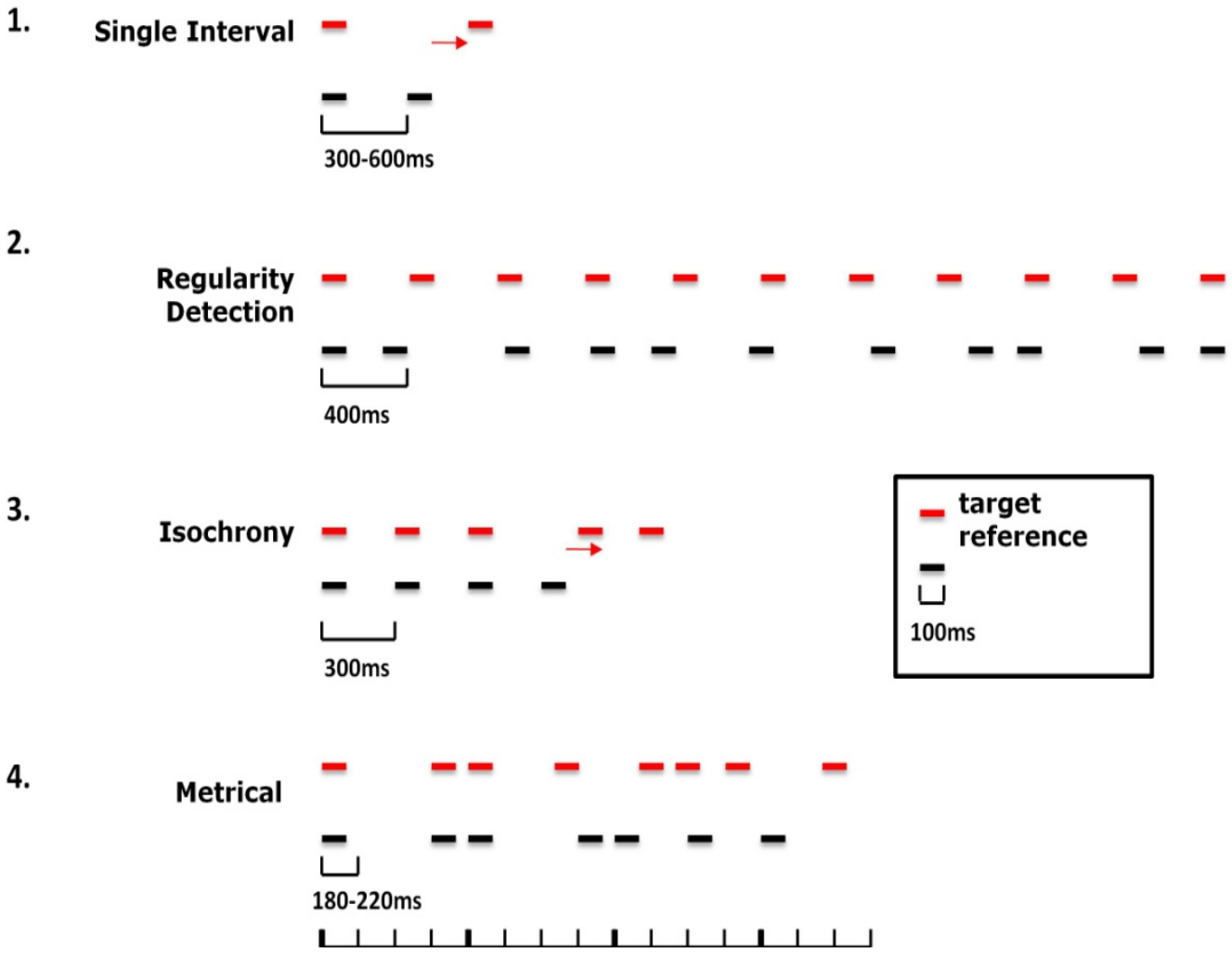
- CB lesions do not affect relative timing (Grube) or emergent timing (Ivry)

- Striatal lesions affects both relative and absolute timing:

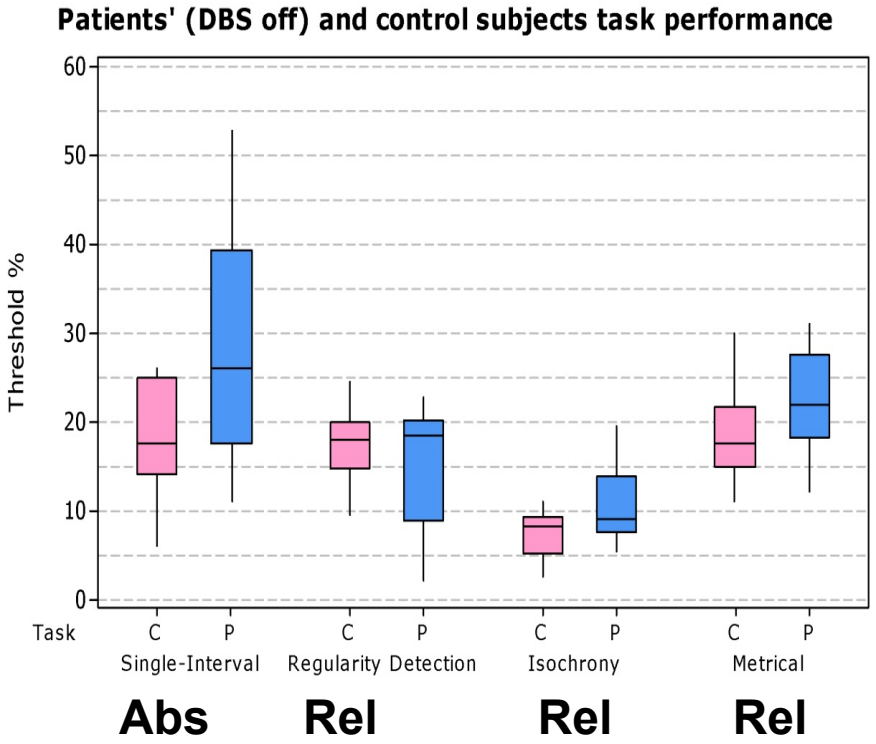
    1) **Parkinson's disease**

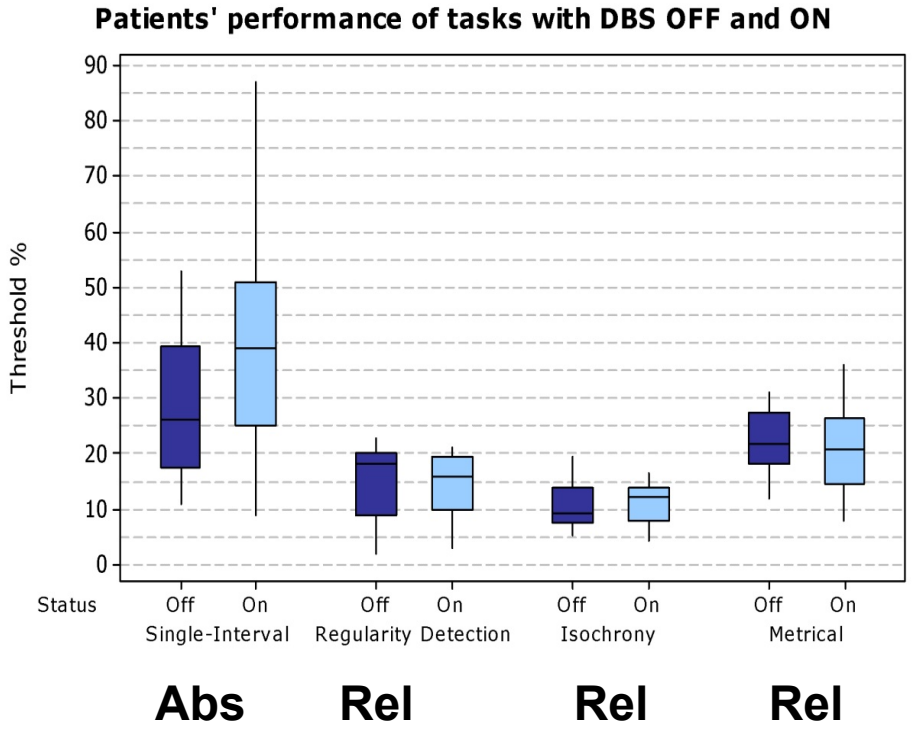
    2) **Huntington's disease and Multiple Systems Atrophy**

I. PD patients



I. PD patients



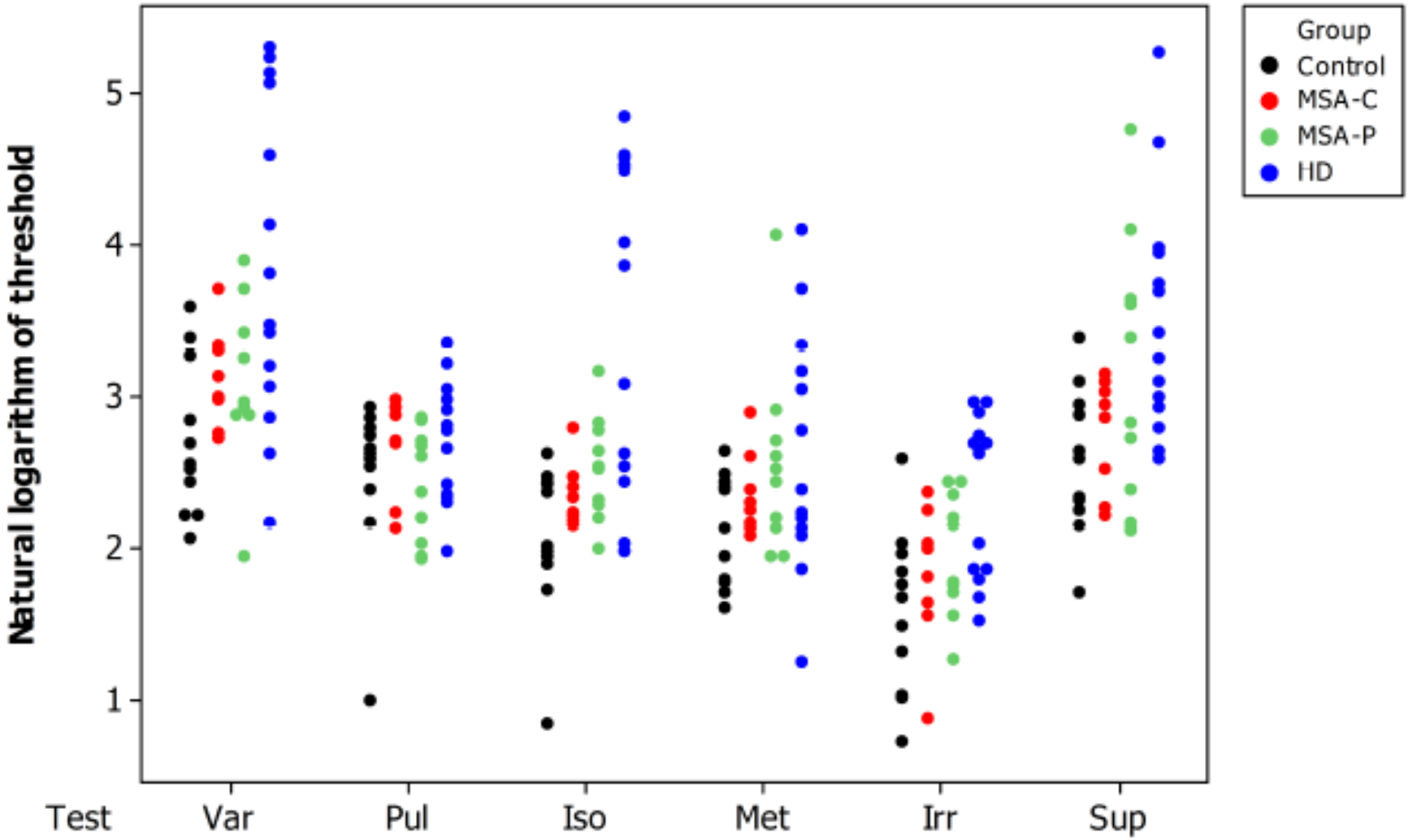


- PD (DBS OFF) worse than controls on single-interval discrimination (abs task)
- PD (DBS ON) worse than PD (DBS OFF) on same absolute timing task

➢ **PD patients also impaired on absolute timing tasks**

Mandal et al., (in prep.)

II. HD/MSA patients



Timing: **Abs** **Rel** **Rel** **Rel** **Abs** **Abs**

II. HD/MSA patients

Figure 2: Mean thresholds by group and task

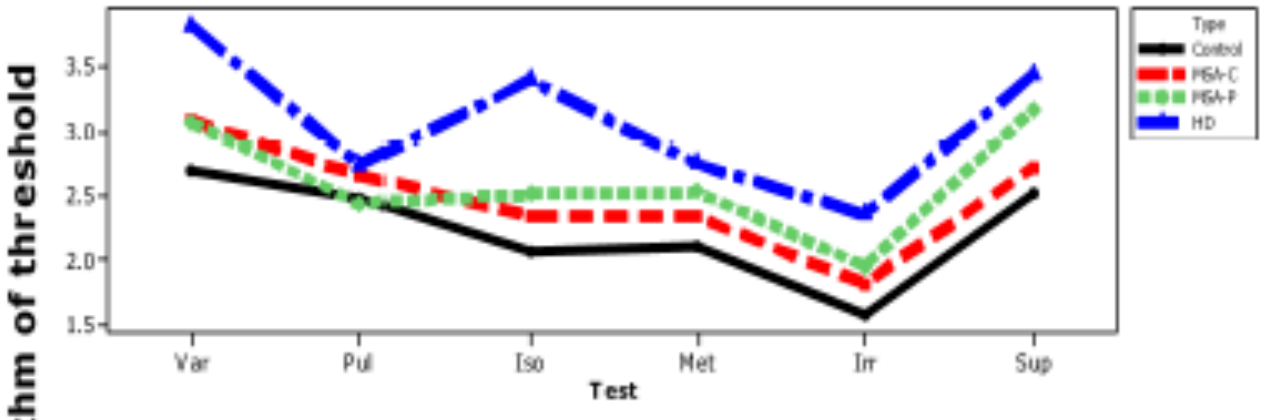
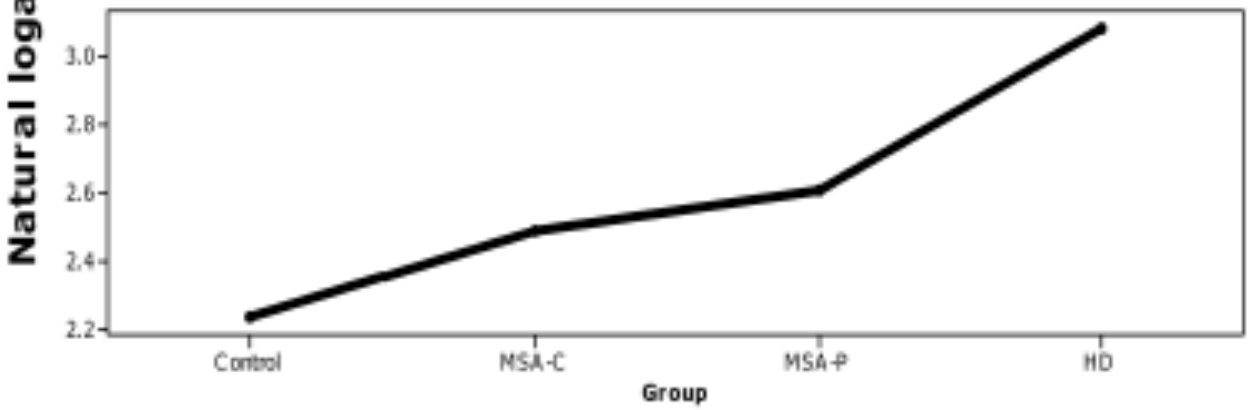


Figure 3: Mean threshold main effects by group



- **HD & MSA-P patients are significantly worse than controls on absolute and relative timing tasks**

Cope et al., (in prep.)

Model summary

- Unified model emphasizes projections between CB and BG which were earlier looked at in isolation wrt interval timing
- Model is asymmetrical in that BG clock (and relative timing) is default mode
- Patients with striatal lesions (PD, HD, MSA-P) impaired on both absolute and relative timing tasks
- Patients with cerebellar lesions impaired only on event-based and not emergent timing tasks
- Understanding timing through such disorders may provide key insights.

Acknowledgments

Manon Grube

Sukhbinder Kumar

Tim Griffiths

wellcome trust