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Neurobiological bases of auditory time perception

Auditory Cognition Group
Wellcome Trust Centre for Neuroimaging

Outline

- Timing substrates
- Duration-based vs. Beat-based timing
- Unified Model of timing
- Summary

I. Timing substrates

SENSORY CORTEX

HIPPOCAMPUS

PREFRONTAL CORTEX

SMA/PRE-SMA

BASAL GANGLIA

CEREBELLUM

Cerebellum and Timing

- Cerebellum is critical for behaviour requiring real-time prediction.

- First proposed as a core timer in millisecond range by Braitenberg (1967).

- Llinas and Yarom further propounded role of cerebellum and inferior olive in timing.

- Patients with cerebellar lesions impaired on motor (e.g. tapping) and perceptual (e.g. duration discrimination) timing tasks with an explicit event-based structure.

cf. Ivry, Spencer, Diedrichsen

Basal ganglia and Timing

- Parkinson's patients are impaired on time perception and production tasks, implicating the nigrostriatal dopaminergic system.

cf. Artieda, Pastor, Harrington, Jahanshahi

- Neurophysiological work in animals trained to perform a timing task implicates nigrostriatal dopaminergic neurons.

cf. Meck, Rammsayer

- Recent recordings in macaques also suggests critical role of striato-thalamo-cortical networks in time perception.

cf. Graybiel, Merchant

II. Timing Mechanisms

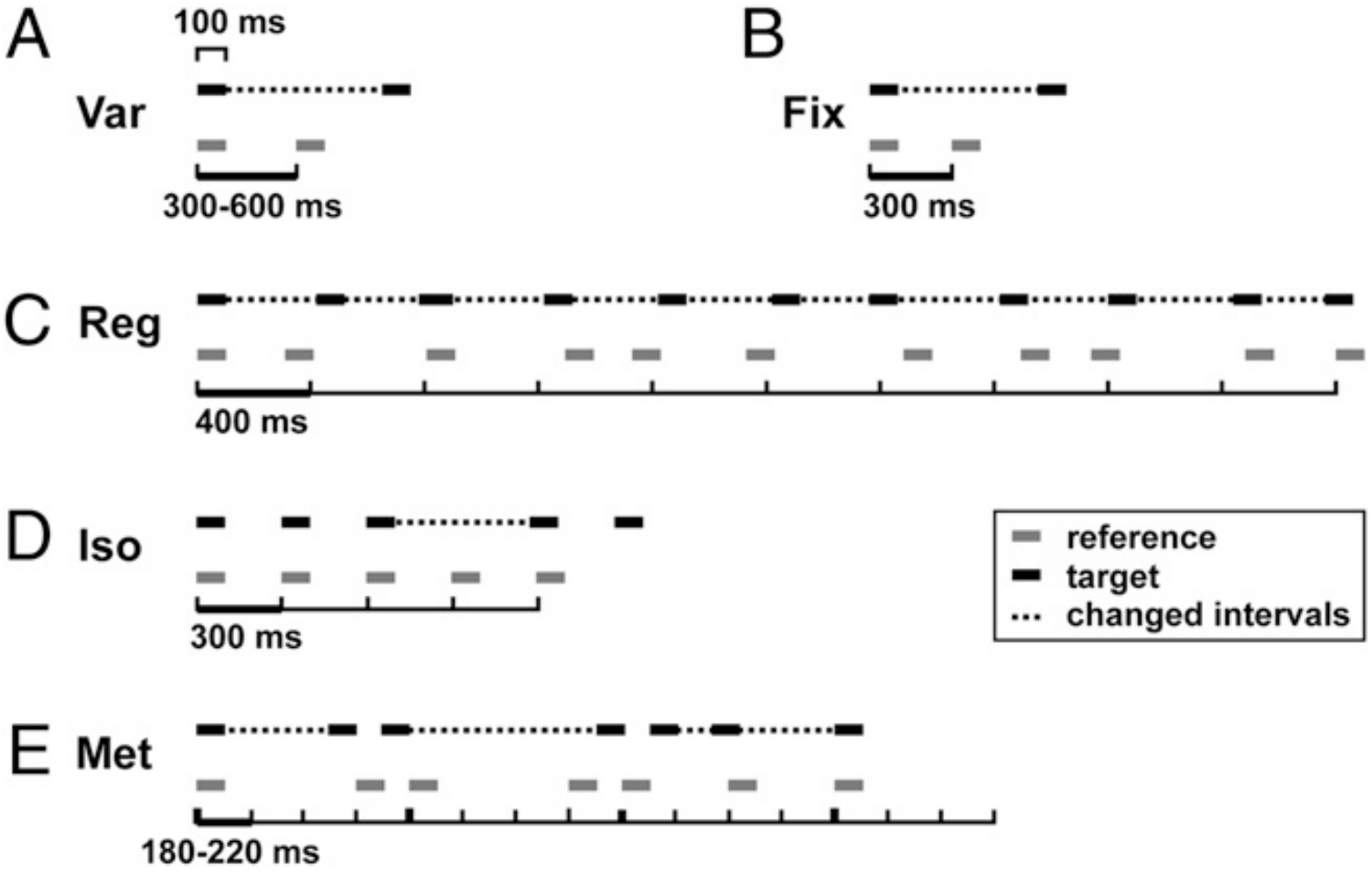
- **Absolute, duration-based timing:**

  Encoding absolute duration of individual time intervals (ΔT_i)

- **Relative, beat-based timing:**

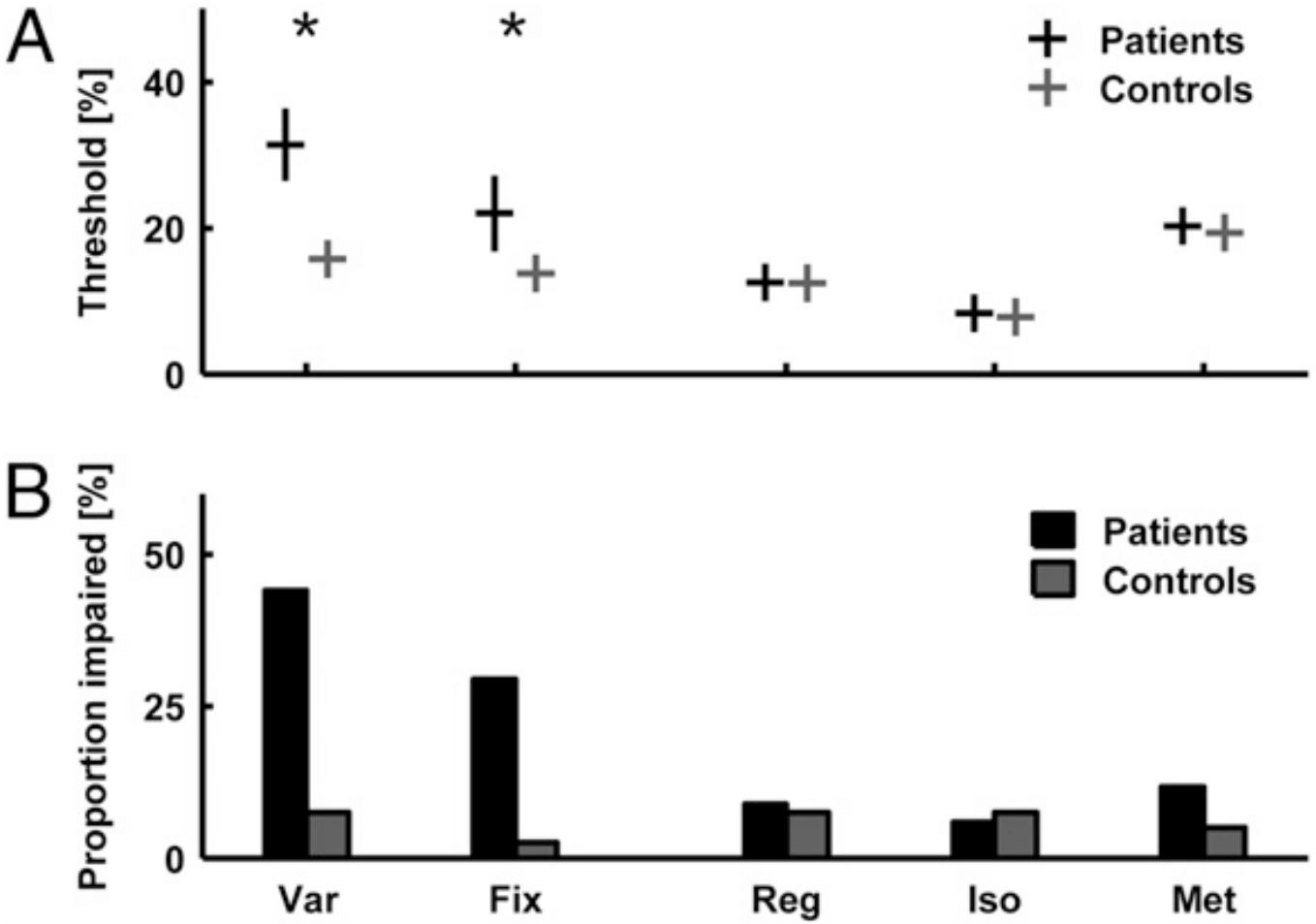
  Timing of intervals relative to a regular beat (ΔT_i / T_{beat})

Duration-based timing



Duration-based timing

Patients with Spino Cerebellar Ataxia type 6:



(Grube et al., 2010)

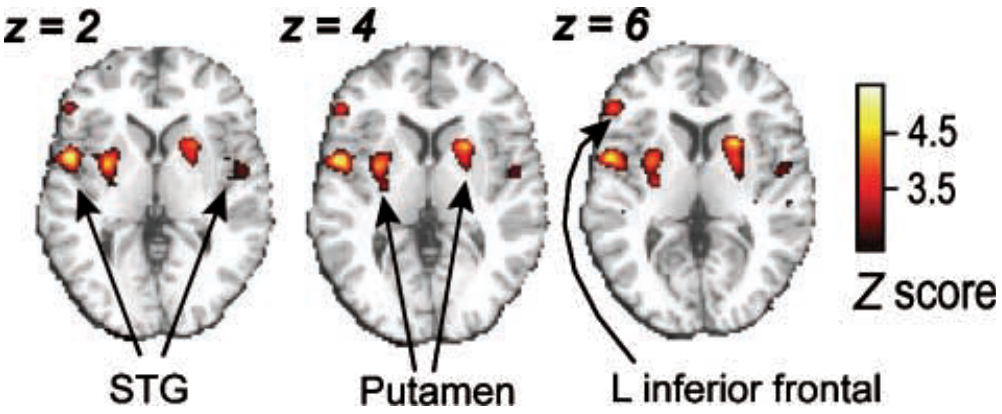
Beat-based timing

A regular beat offers beneficial temporal cues in perceptual timing

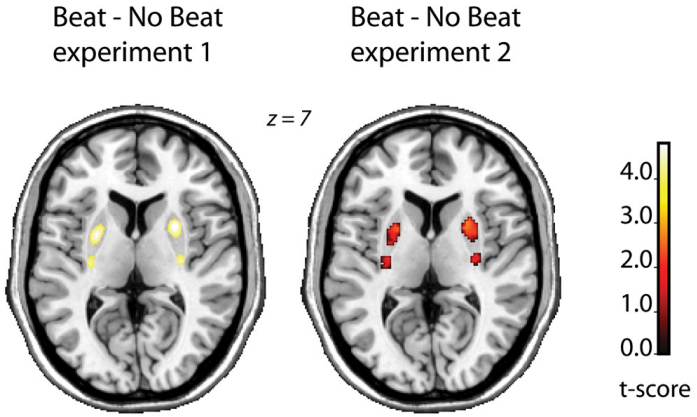
(Povel & Essen, 1985)

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

III. Functional MRI study

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

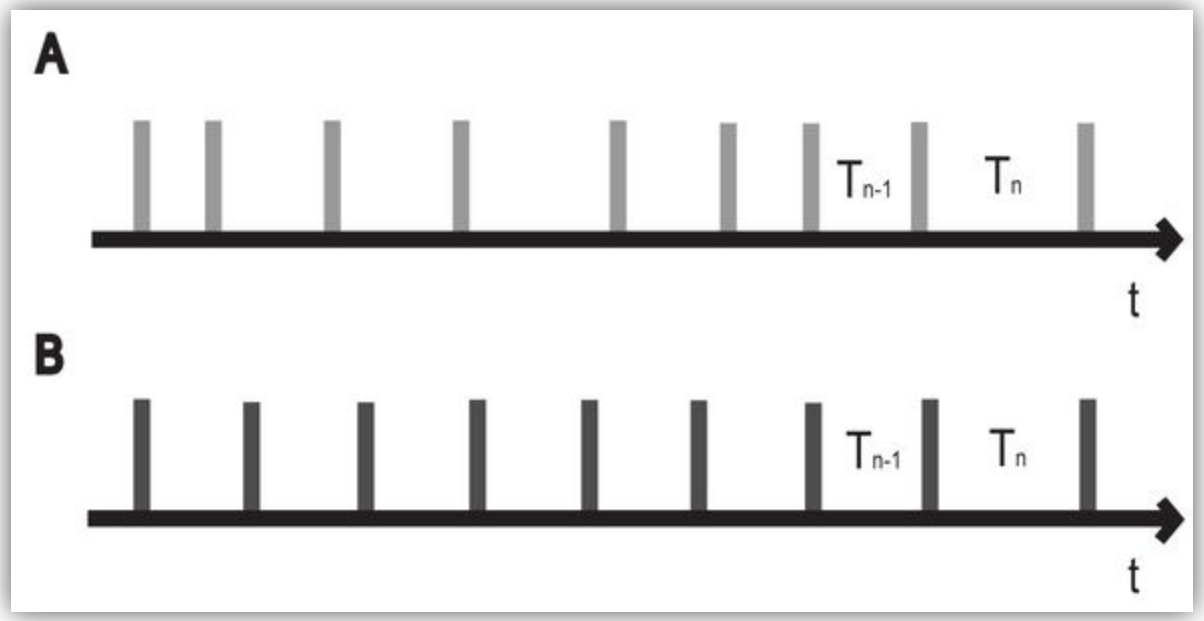
Hypotheses:

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

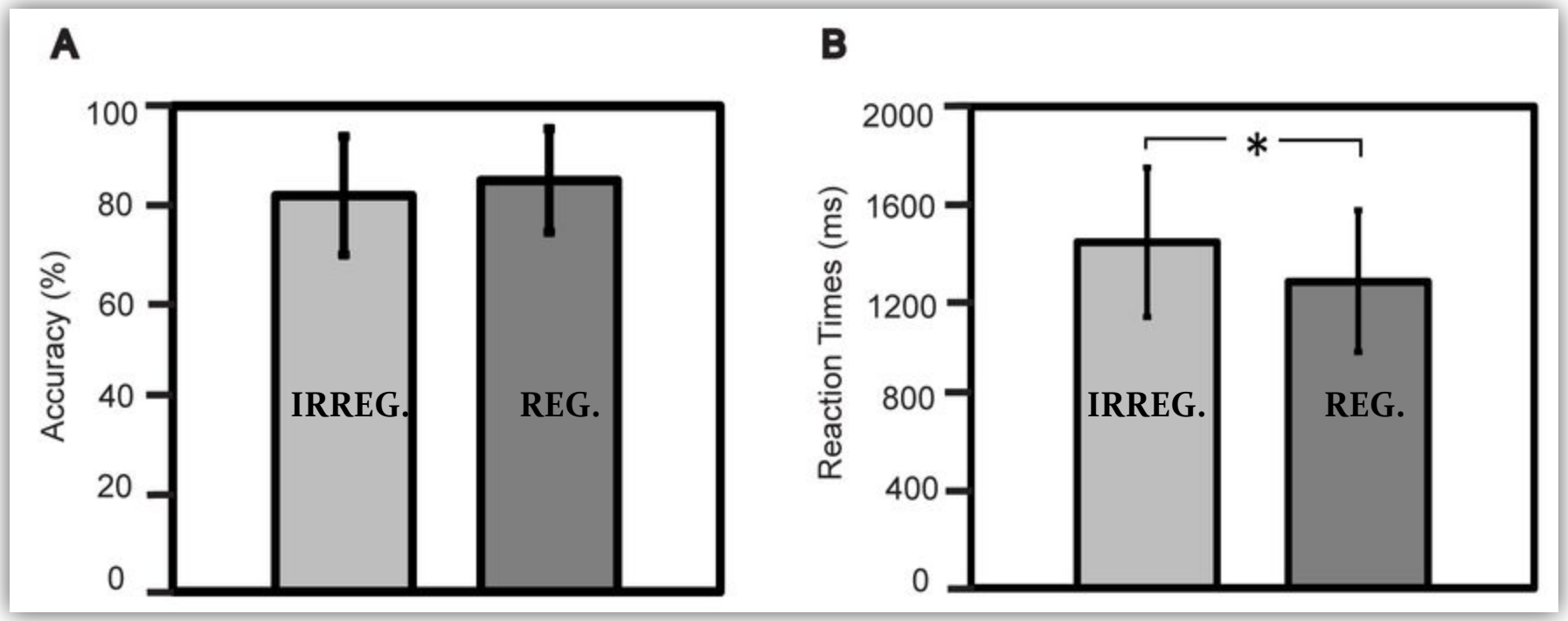


- ***Judge the duration of the final compared to the penultimate interval***
  T_n > / < T_{n-1}

Sequence A: Irregular with 15% average jitter

Sequence B: Regular with an isochronous beat

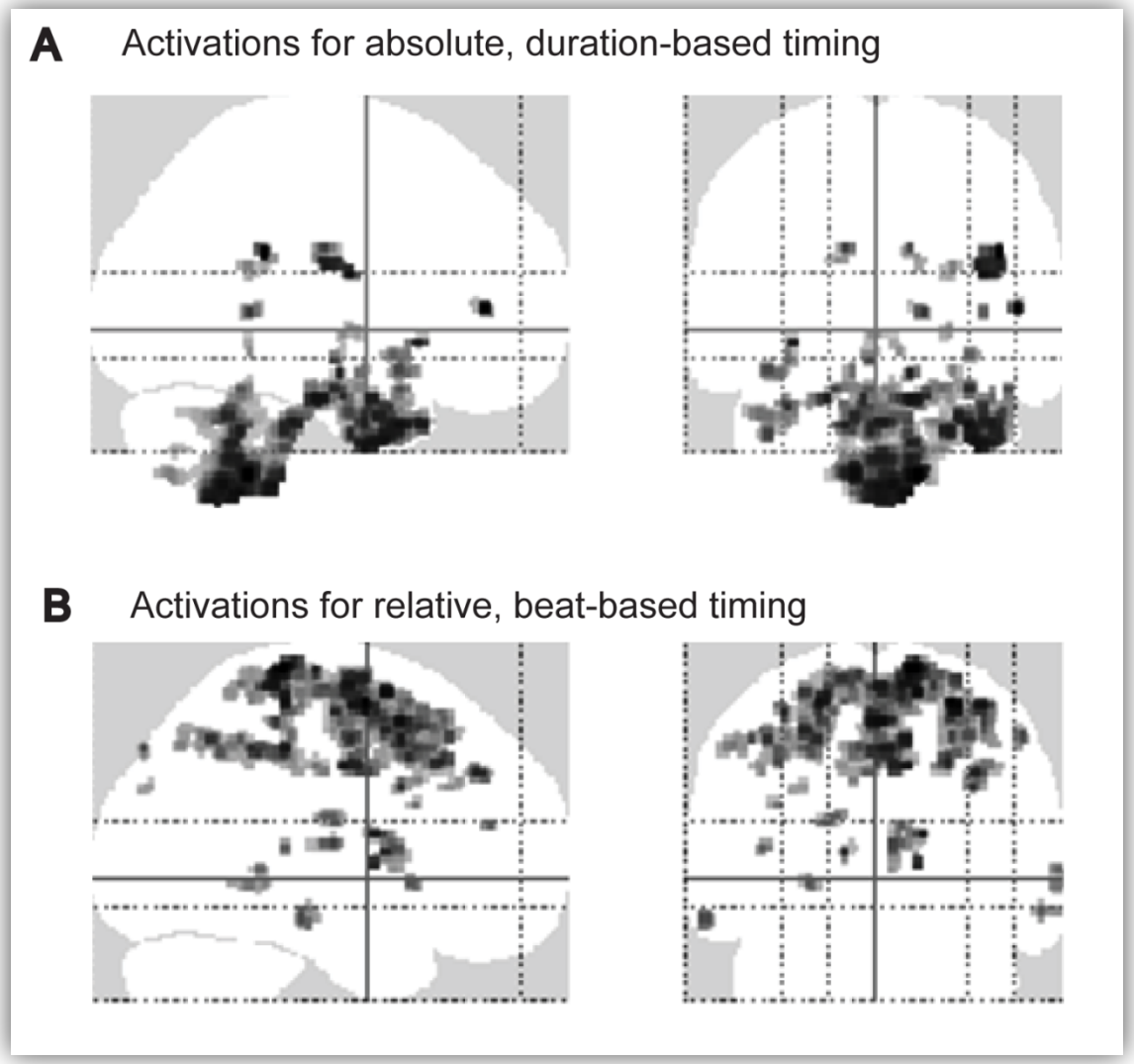
Behaviour in scanner



81.53% **84.72%**
± 12.28% ±10.64%

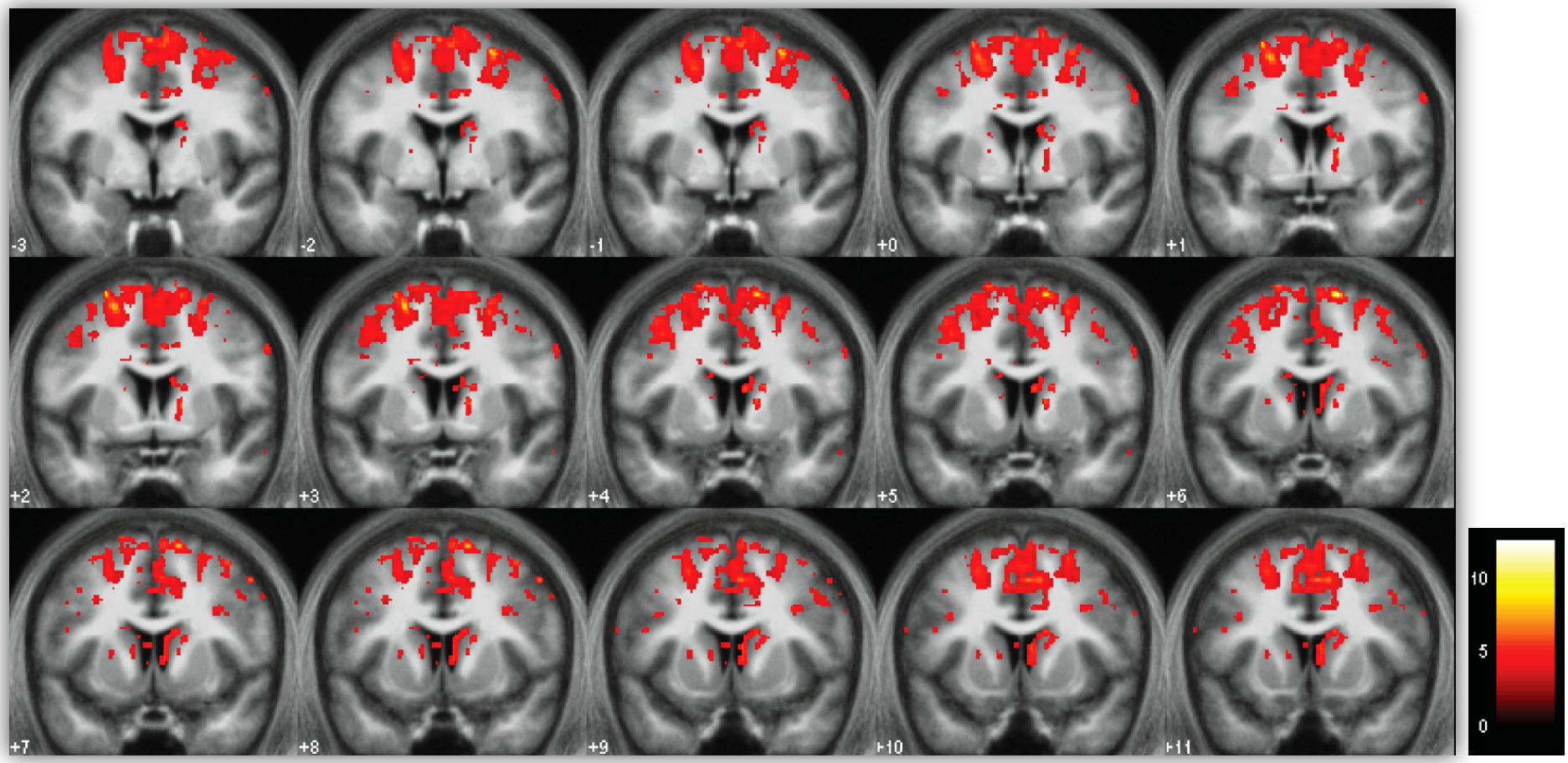
1438 **1275**
± 297 ms ± 312 ms

fMRI results



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

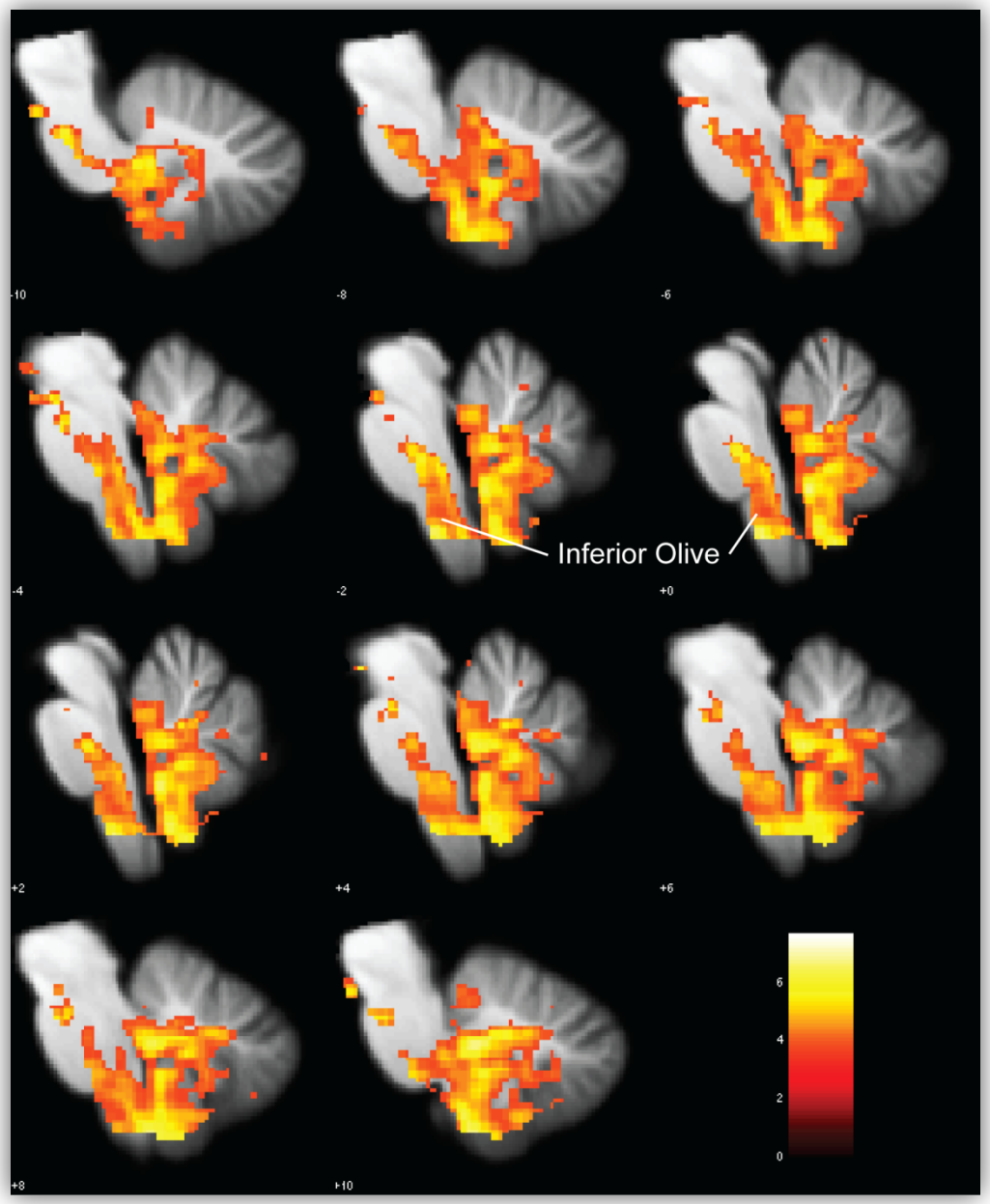
Fronto-striatal activations



x = -3 mm to + 11 mm

p < 0.001 (unc.)

Olivocerebellar activations

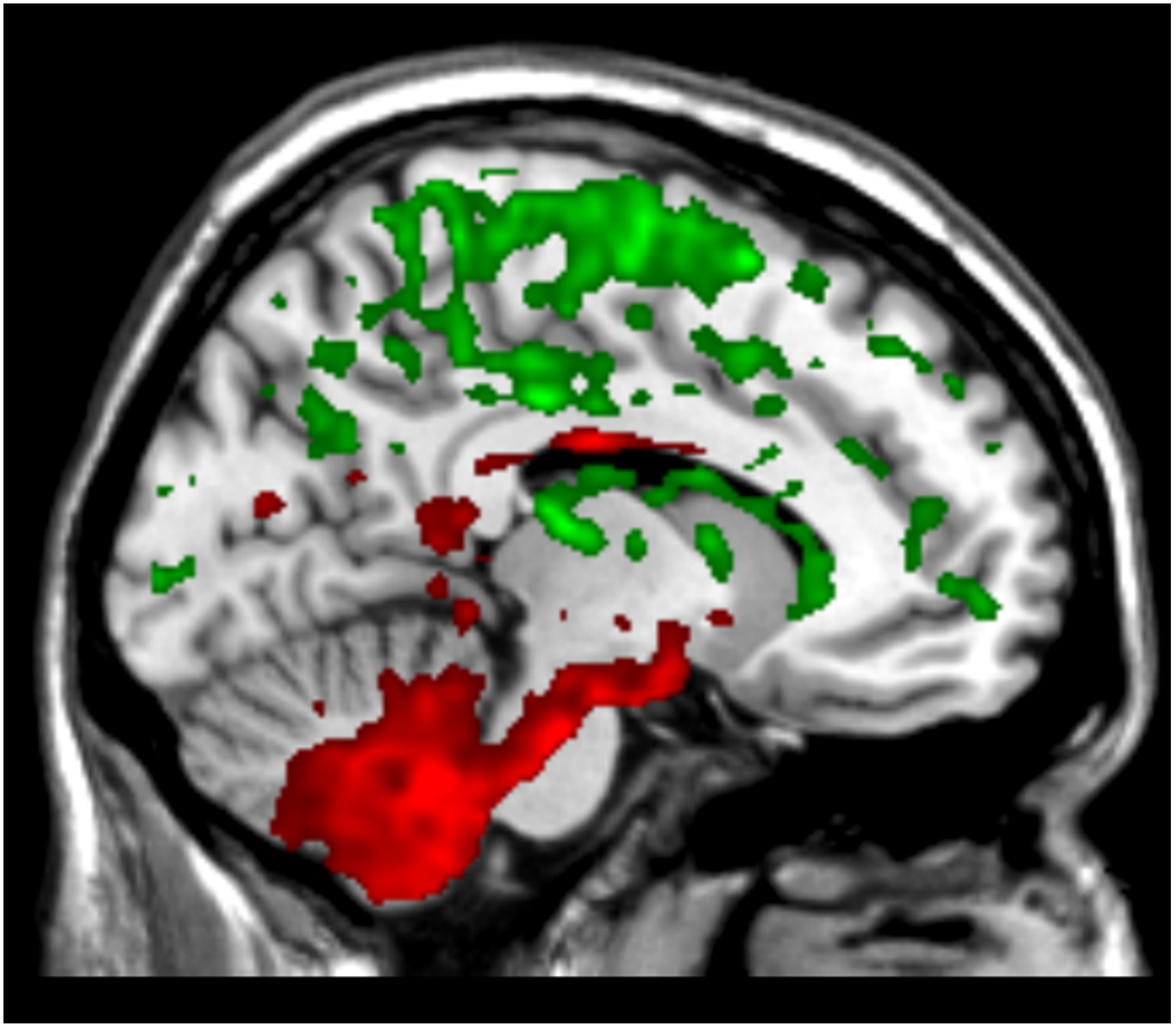


p < 0.001 (unc.)

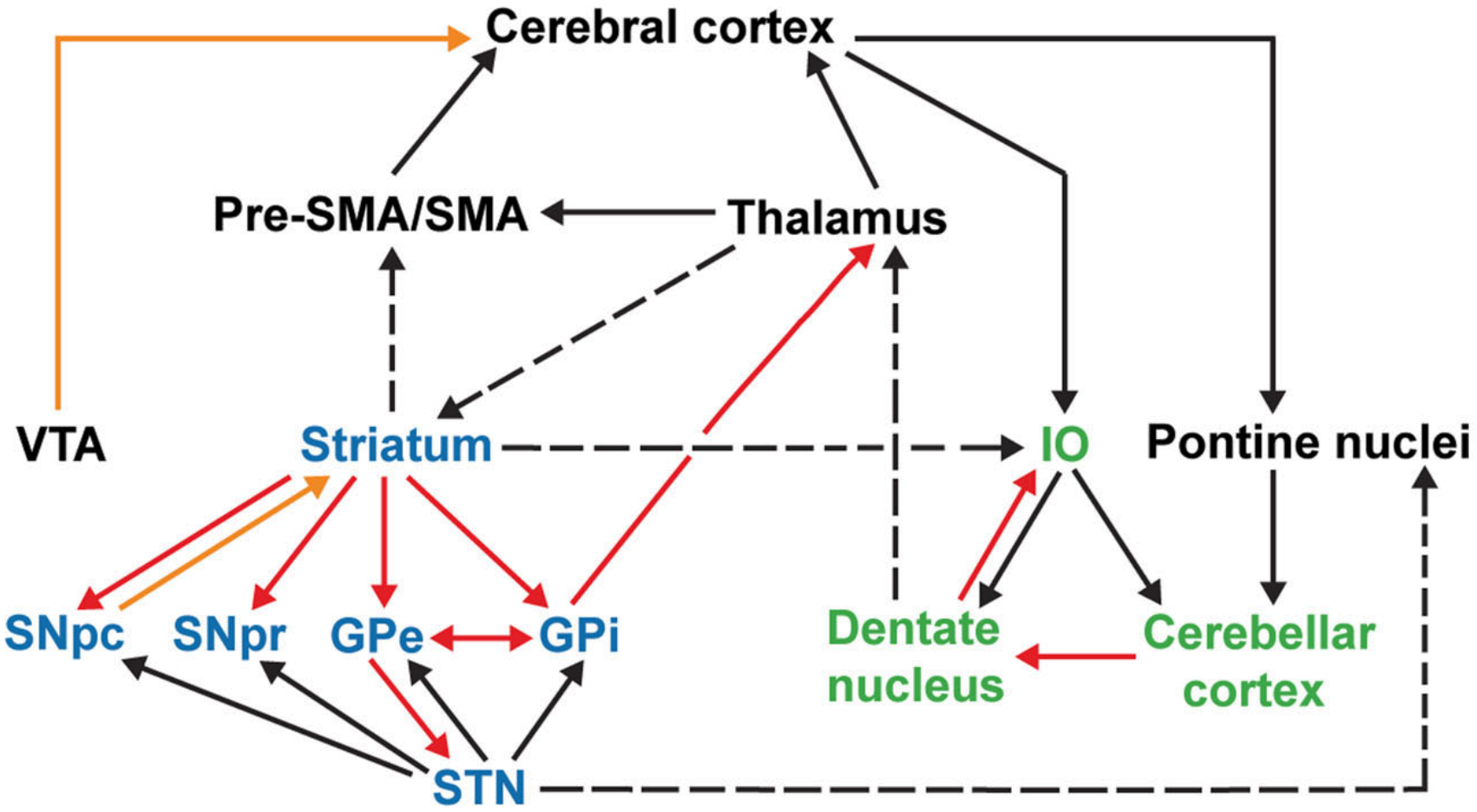
x = -10 to +10 mm

Teki et al., 2011
J Neurosci

Functional dissociation



IV. Unified model of timing



Teki et al., 2012
Allman,Teki et al., 2014

Unified model: features

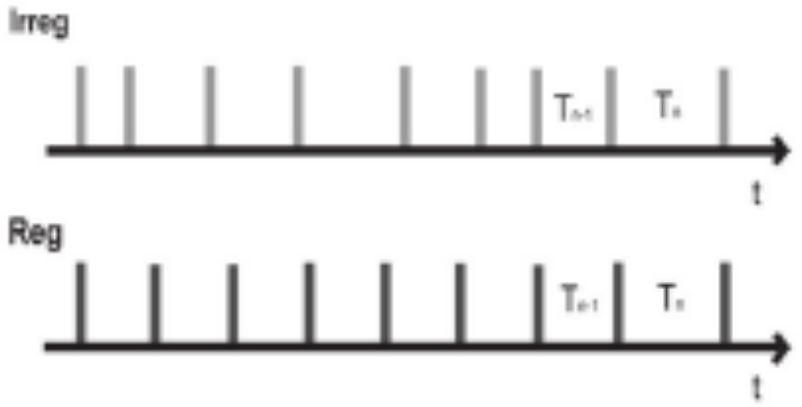
- Motor structures specialized for timekeeping in the brain
- Timing functions of BG and CB not necessarily independent
- BG network timing signal based on Striatal Beat Frequency model (Meck)
- CB network timing signal based on known neurophysiology
- The two key networks interact to improve the accuracy 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: mechanism

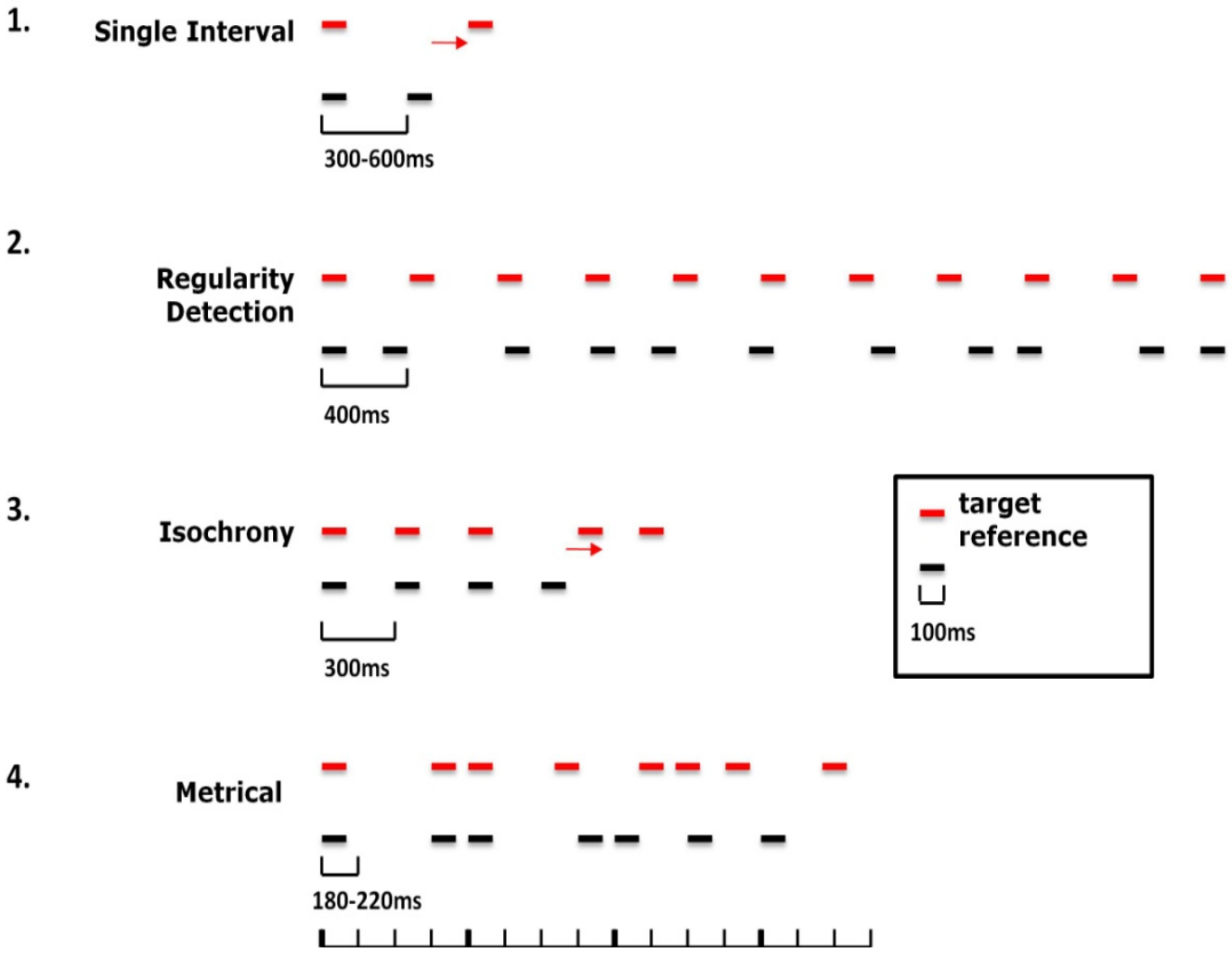
- **Function**: beat-based timing with error-correction by duration-based clock



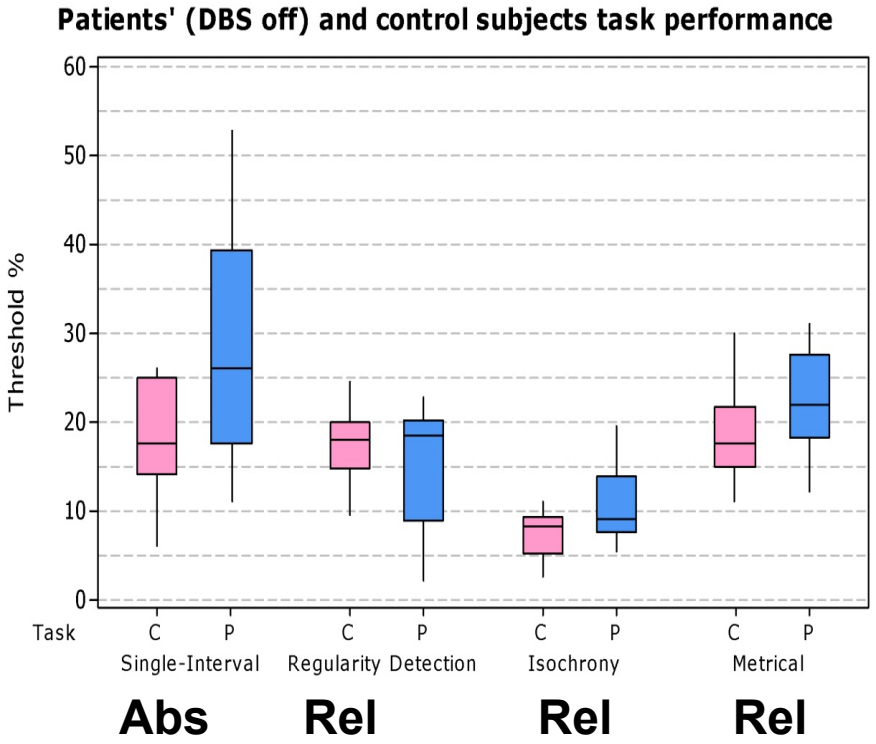
Regular context:
beat-based clock produces less errors in predicting next time intervals =>
less error-correction required and lesser contribution of CB clock

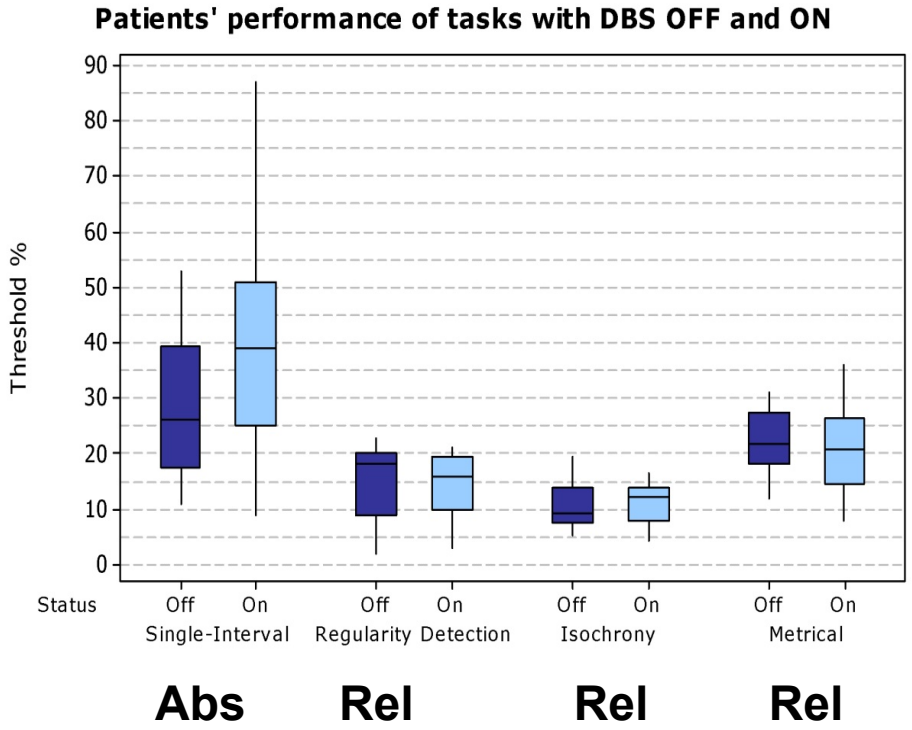
Irregular context:
beat-based clock produces larger errors in predicting next time intervals =>
greater error-correction required and more contribution by CB clock

I. Parkinson's patients



I. Parkinson's patients



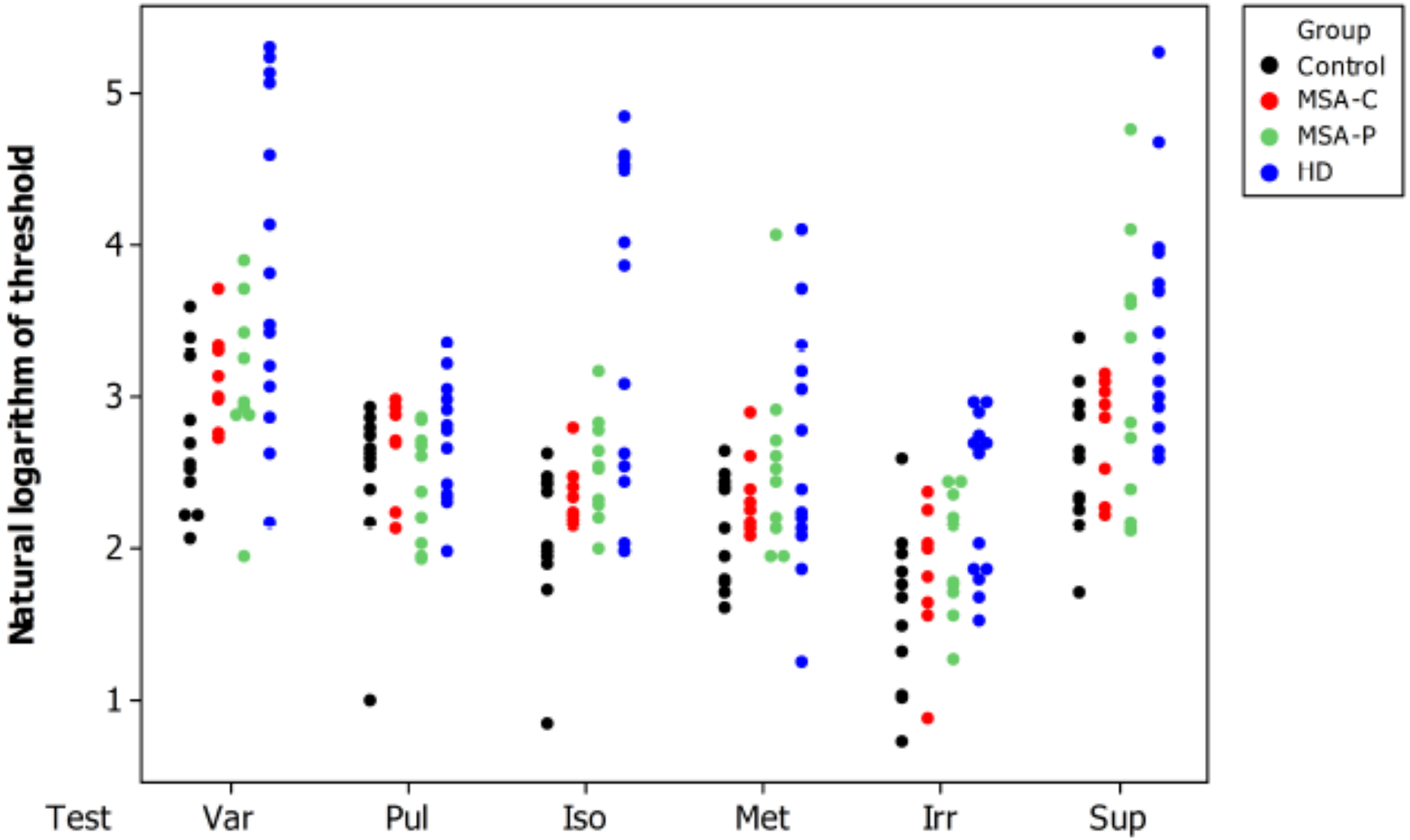


- PD (DBS OFF) worse than controls on single-interval discrimination (abs task)
- PD (DBS ON) worse than PD (DBS OFF) on same absolute timing task

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

Mandal et al., (in prep.)

II. Huntington's and MSA patients



II. Huntington's and MSA patients

Figure 2: Mean thresholds by group and task

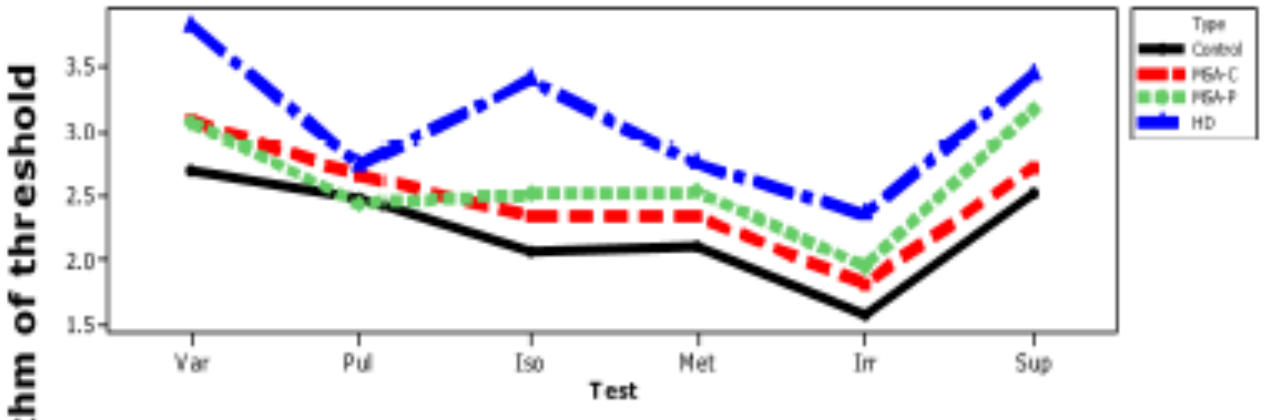
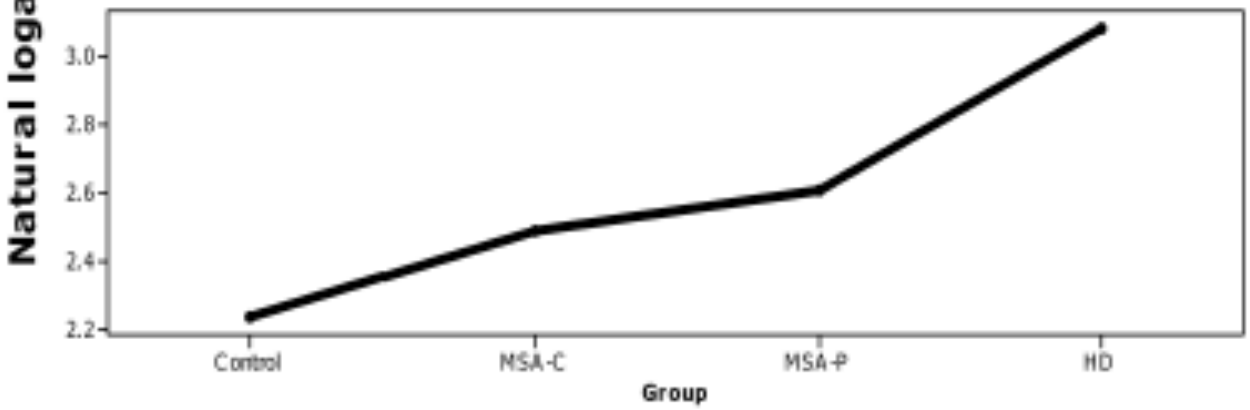


Figure 3: Mean threshold main effects by group



- HD patients significantly worse than controls on absolute and relative timing tasks
- MSA-P also significantly worse than controls on absolute and relative timing tasks

Cope et al., 2013

Unified 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 CB lesions impaired only on event-based and not emergent timing tasks
- Understanding timing through such disorders may provide key insights.

Overall summary

Time is a distributed property of brain circuits but certain structures are specialized for temporal processing.

Rhythmic structure of time intervals is an important dimension in the analysis of time intervals, especially in auditory domain for signals such as speech and music.

Substrates involved in timing may have separate roles (attention/memory) but the dorsal striatum appears to be vital for supporting core timing functions.

Disorders that are associated with impairment in timing analysis can give us a view into the systems level deficits.

Acknowledgments

Tim Griffiths

http://www.fil.ion.ucl.ac.uk/~tgriff

http://www.fil.ion.ucl.ac.uk/~steki