Multidimensional cerebellar computations for flexible kinematic control of movements

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Cerebellum

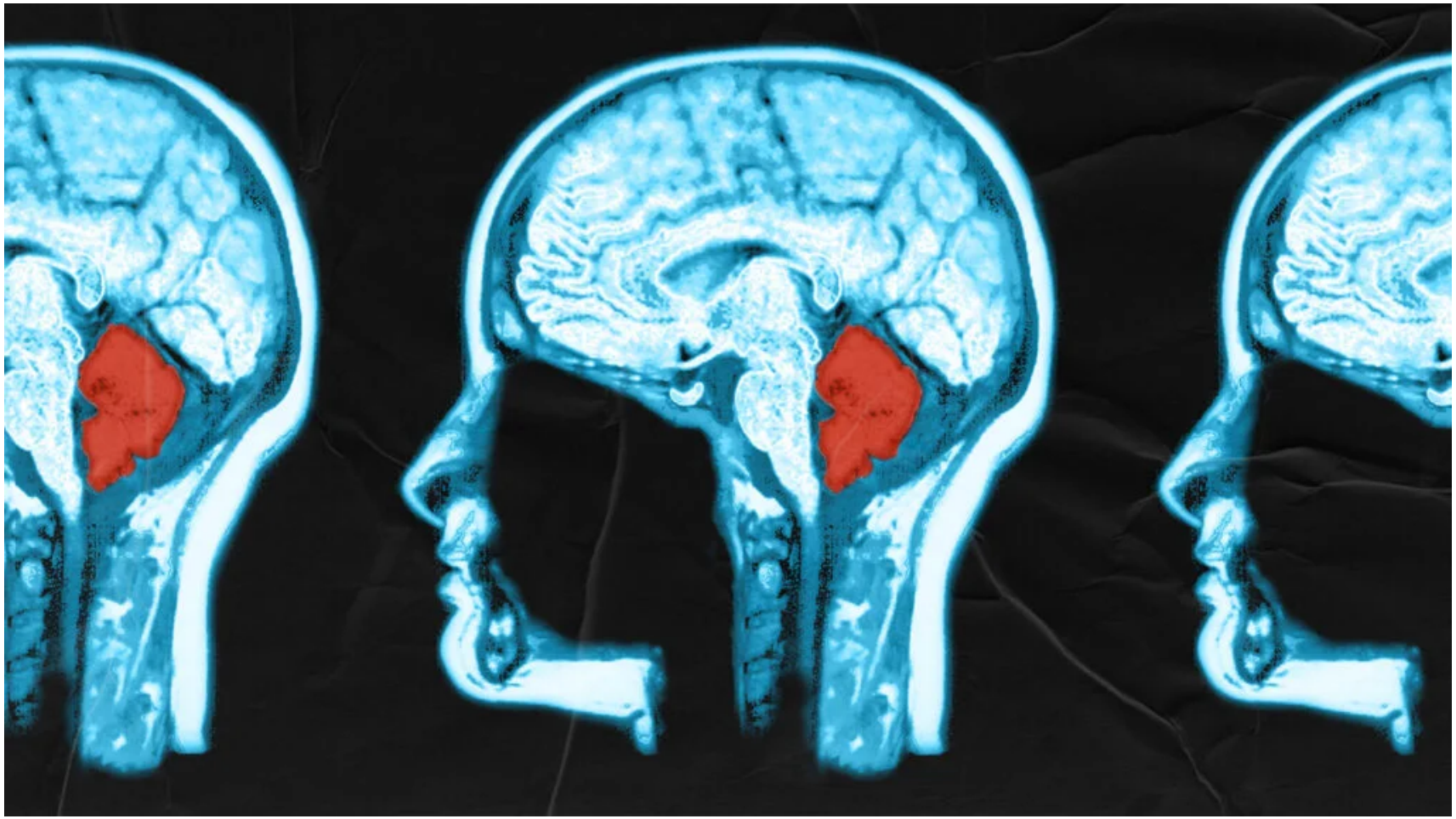


Figure: Cerebellum

Cerebellum Importance

Functions:

- Maintaining Balance
- Coordinating Movement
- Eye Movements
- Learning Movements that require practice and fine-tuning

Disorder:

- Disturbance in Muscle Control
  - → Lack of Muscle Control and Coordination
  - → Difficulties with Walking and Mobility
  - → Slurred Speech or Difficulty Speaking
  - → Abnormal Eye Movements

Extra Reference

Letter | Published: 14 October 2015

Encoding of action by the Purkinje cells of the cerebellum

David J. Herzfeld, Yoshiko Kojima, Robijanto Soetedjo & Reza Shadmehr

Nature **526**, 439–442 (2015) | Cite this article

10k Accesses | **175** Citations | **78** Altmetric | Metrics

Figure: Purkinje cell involvement in vision

Short-term Motor Learning

Short-term motor learning is a type of learning that allows us to quickly adjust our movements in response to unexpected changes in the environment or within ourselves. It's like a rapid adaptability system for our movements.

Examples:

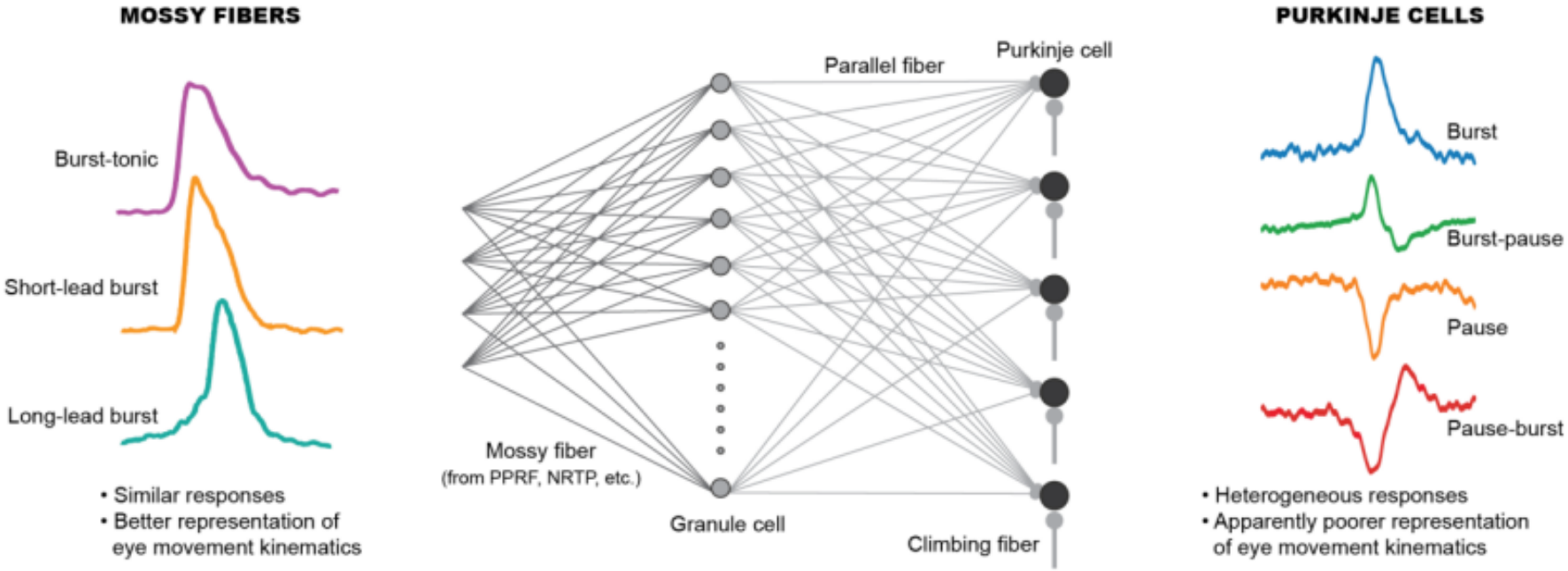
- The motor plant may change due to Muscular Fatigue slowing movements
- Boredom and Declining Motivation, i.e., cognitive fatigue will reduce the speed of movements

Adaptation to external and internal changes involves adjustments of several kinematic parameters

Short-term Motor Learning

How does the cerebellum coordinate the control of multiple kinematic parameters in order to ensure optimal movements?

Spoiler


MOSSY FIBERS
Burst-tonic
Short-lead burst
Long-lead burst
• Similar responses
• Better representation of eye movement kinematics
Parallel fiber
Purkinje cell
Mossy fiber
(from PPRF, NRTP, etc.)
Granule cell
Climbing fiber
PURKINJE CELLS
Burst
Burst-pause
Pause
Pause-burst
• Heterogeneous responses
• Apparently poorer representation of eye movement kinematics

Experiment

Experiment

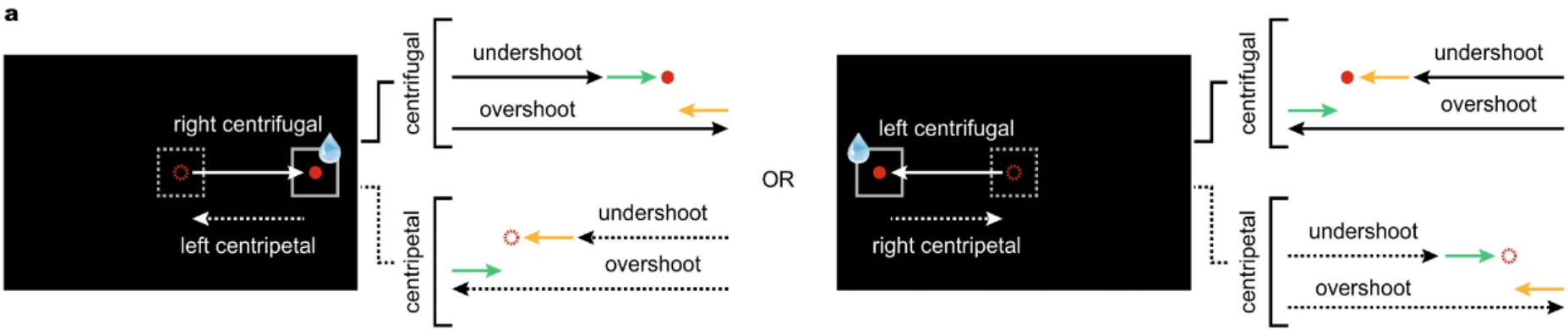


Figure: Behavioral task

Result

The cerebellum performs the necessary multi-dimensional computations for the flexible control of different movement parameters depending on the prevailing context.

This conclusion is based on

→ Identification of a manifold-like activity in both mossy fibres (MFs, network input) and Purkinje cells (PCs, output), recorded from monkeys performing a saccade task.

Literature

Mossy Fibres

- Fine-Tuning of Movements
- Motor Learning

Purkinje cells

They are inhibitory neurons

- Refine Motor Movement
- Maintain Balance and Posture
- Implicated in Motor Learning

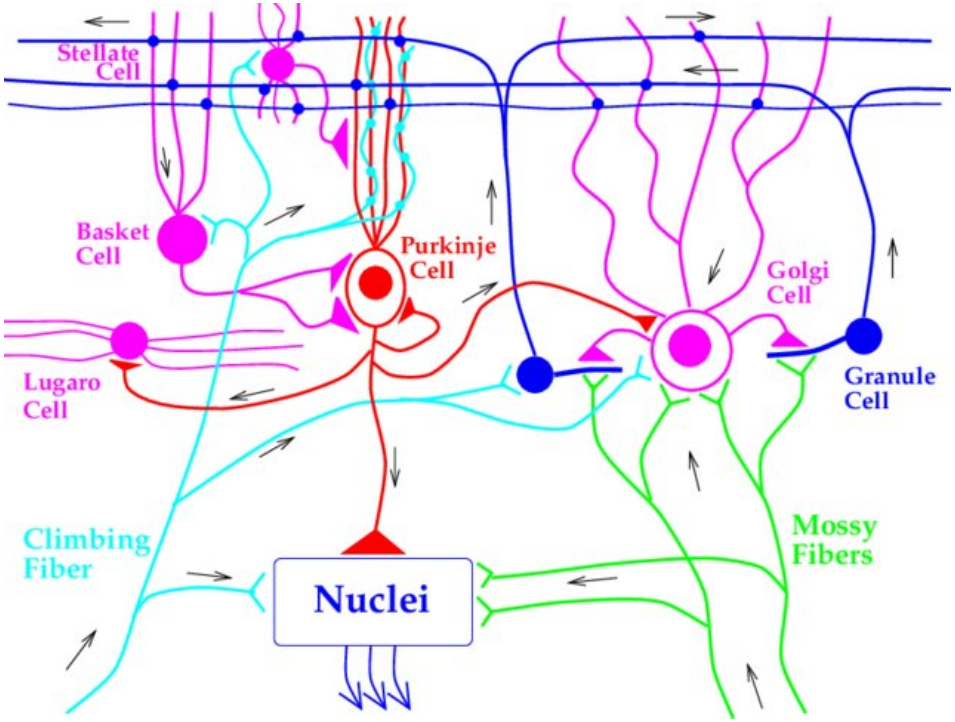


Figure: MF and PC

Velocity-Duration Adjustments During a Fatigue-Inducing Repetitive Saccade Task

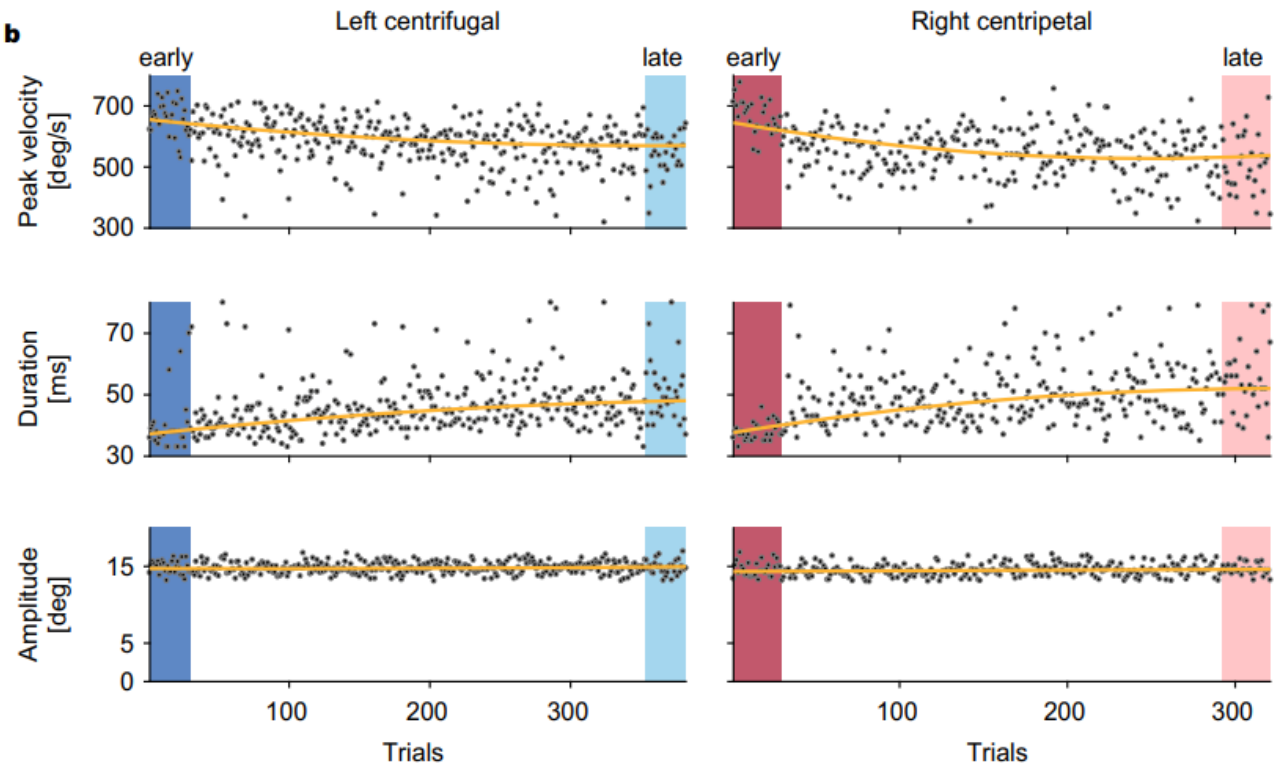


Figure: Gradual drop in saccade velocities was compensated by a likewise gradual upregulation of saccade duration

Mossy Fibre Discharge Encodes Saccade Kinematics

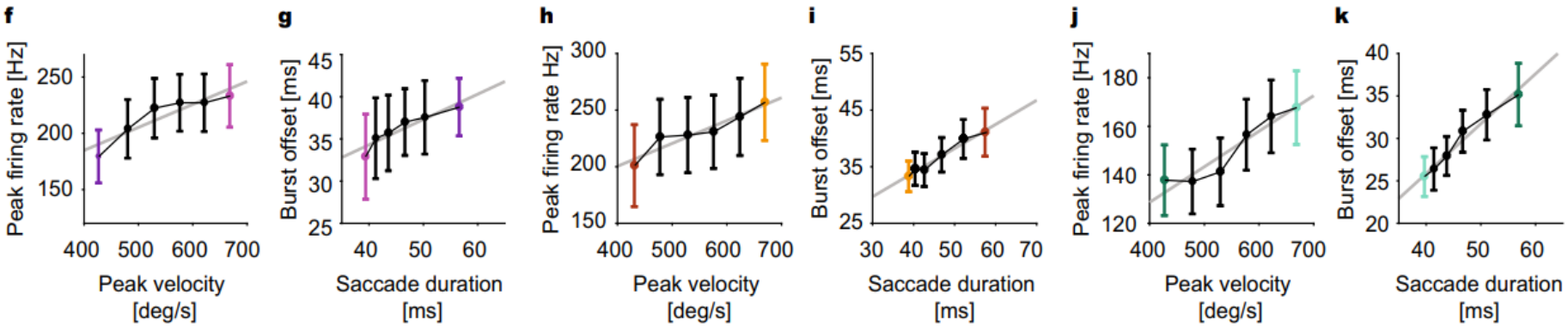


Figure: The peak discharge rate grew linearly with PV over the full range of PV bins, whereas the time of burst offset linearly predicted the time of saccade offset

Classification of Mossy Fibre Responses

Three main categories for the responses of mossy fibers (MFs) in relation to saccadic eye movements:

- Burst-Tonic Type
- Long-Lead Burst Type
- Short-Lead Burst Type

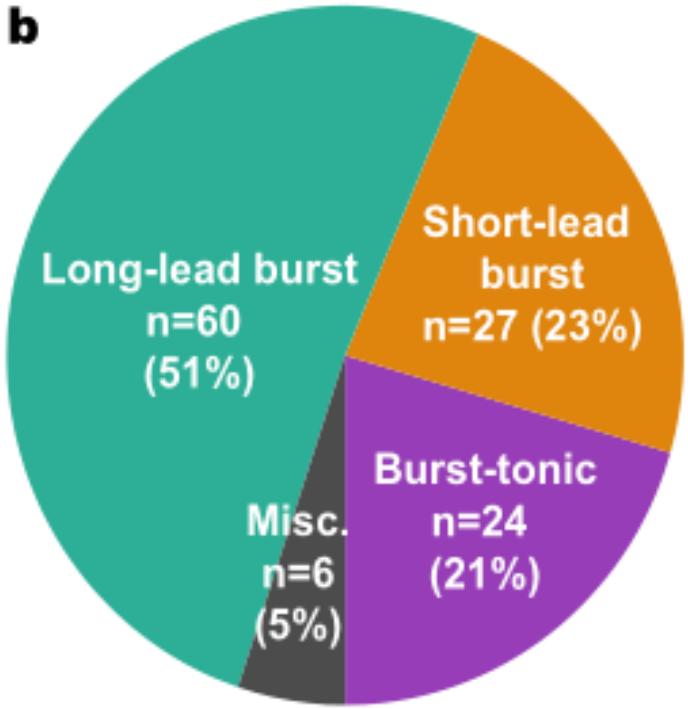


Figure: Proportion of MF units in each category

Classification of Mossy Fibre Responses

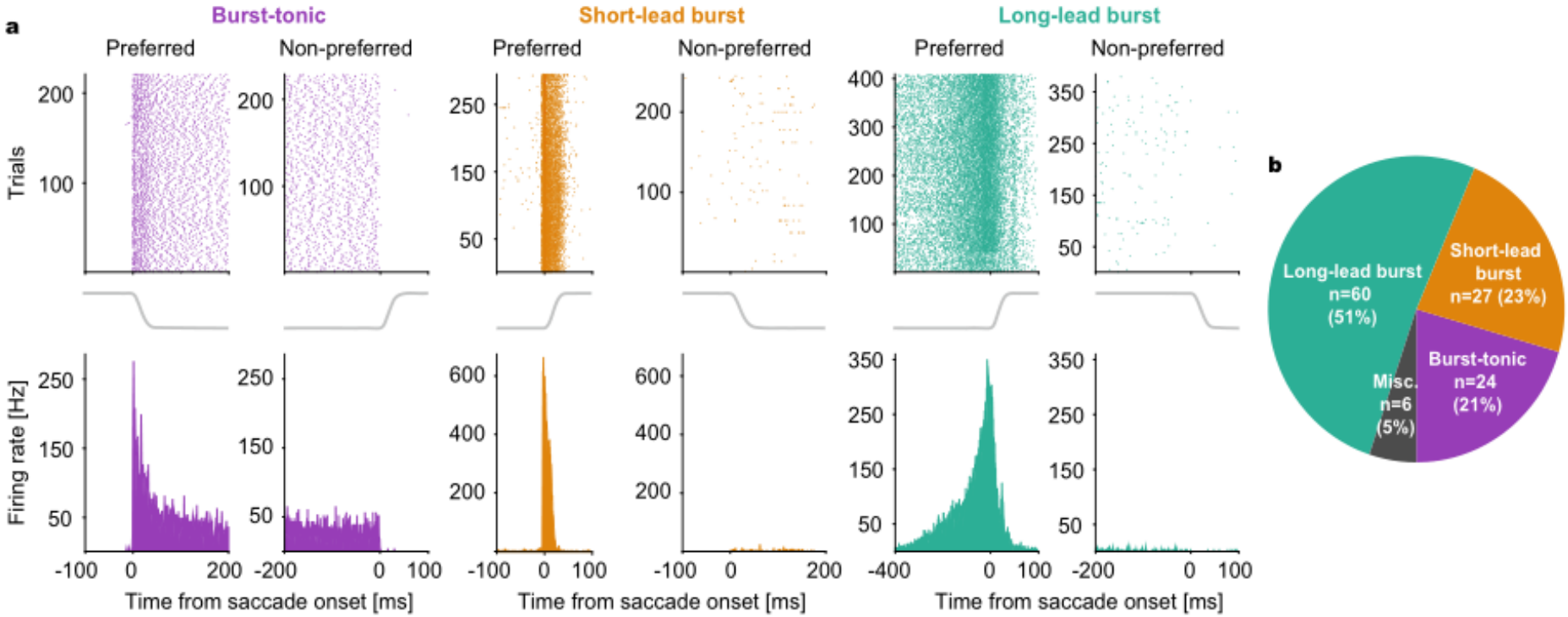


Figure: Encoding of saccade kinematics by mossy fibers (MFs)

Classification of Mossy Fibre Responses

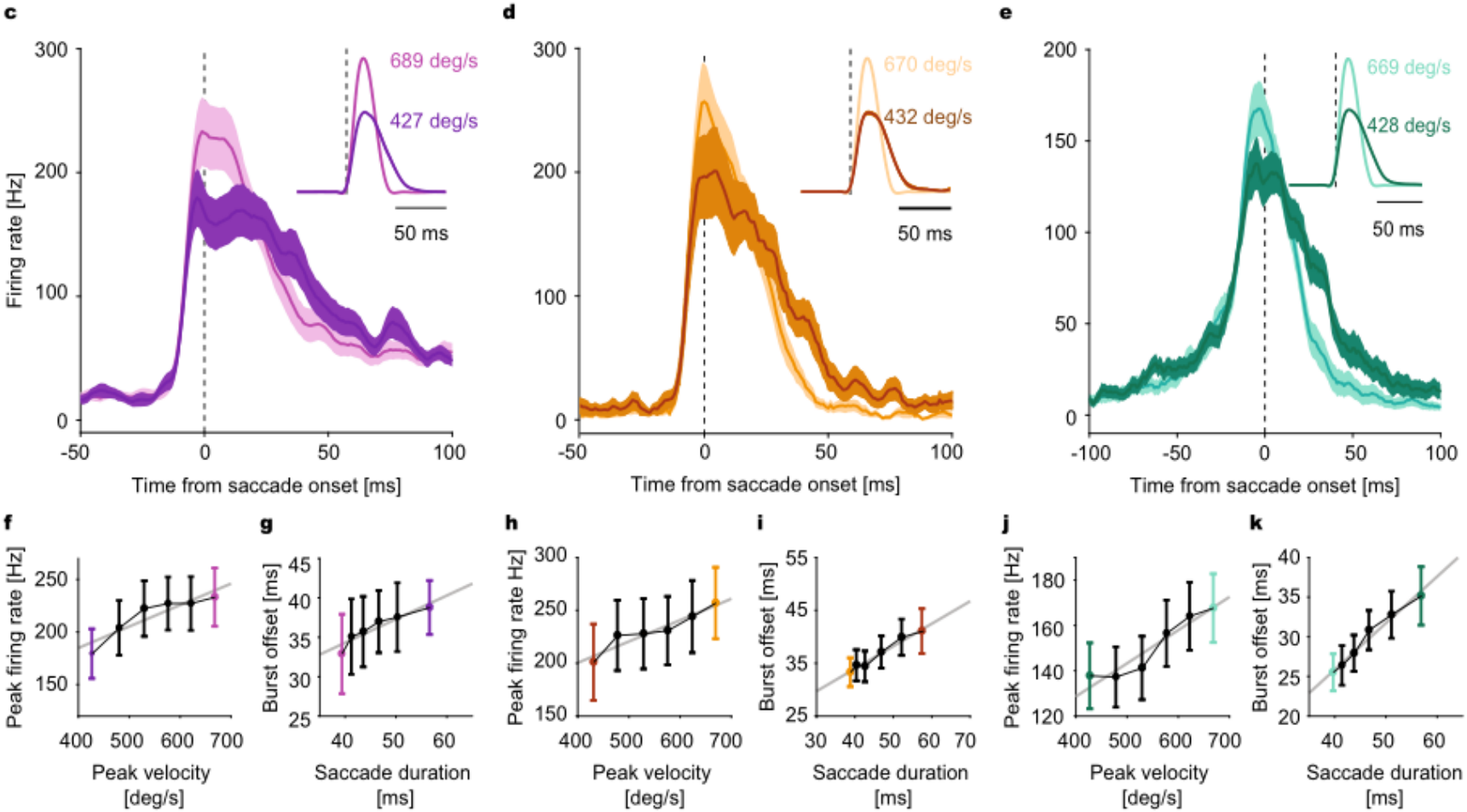


Figure: Encoding of saccade kinematics by mossy fibers (MFs)

Simple Spikes of Purkinje Cells Encode Saccade Kinematics

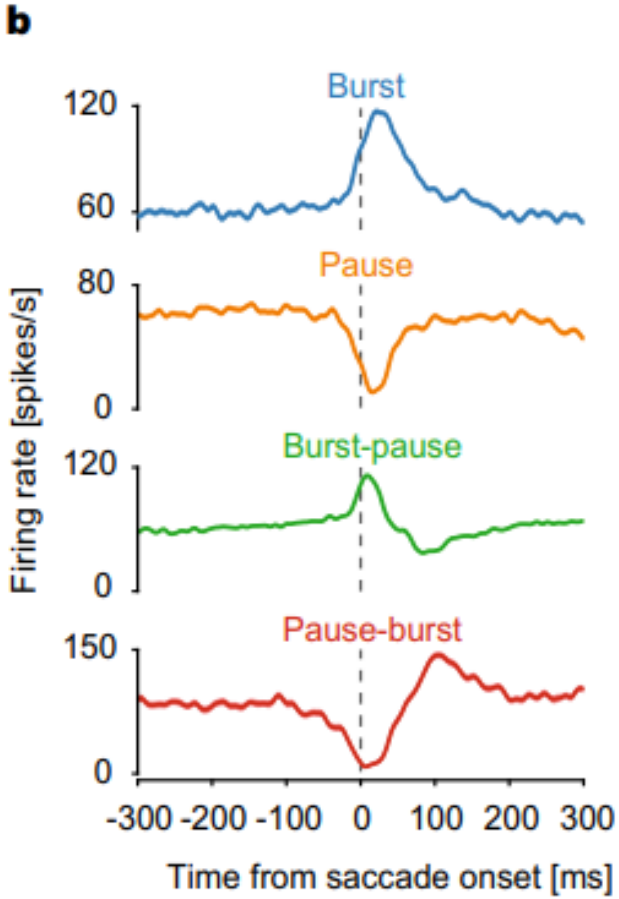


Figure: the SS discharge of PCs in our data set encoded both movement velocity and duration, albeit not as precisely as in the case of MFs

Extra Reference

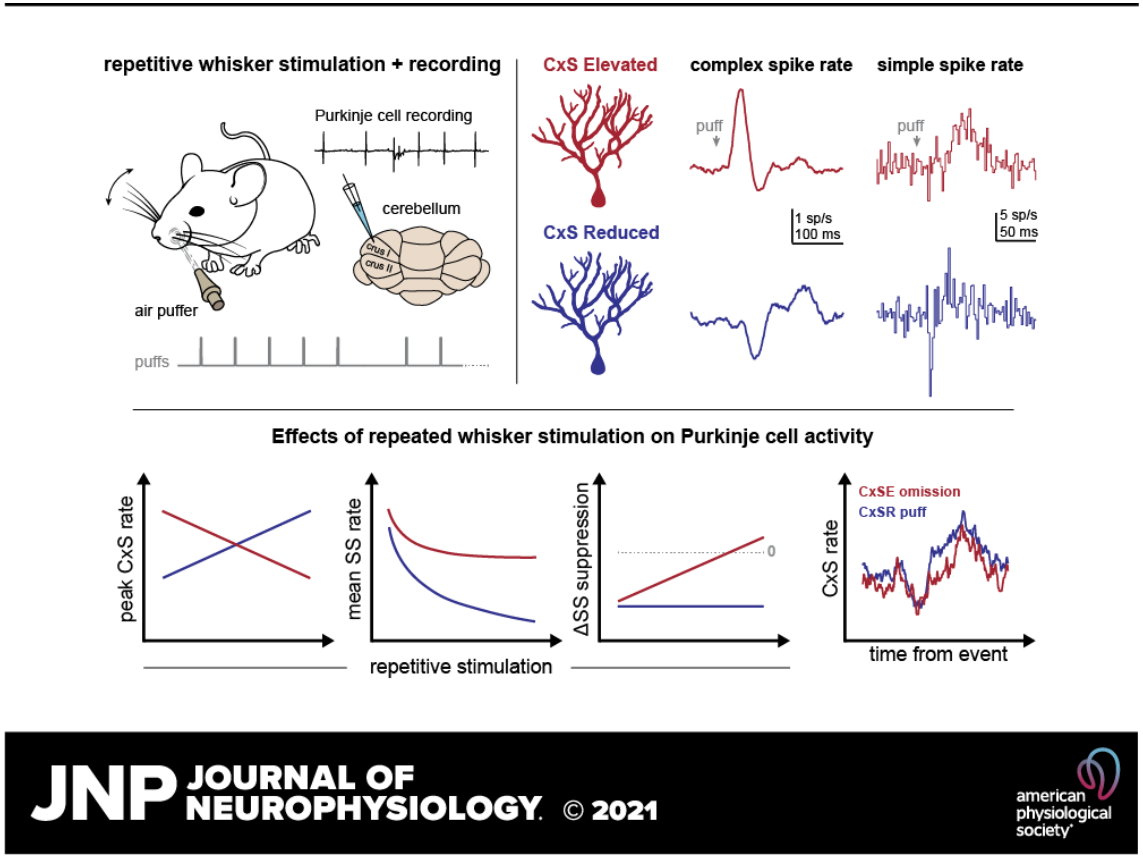


Figure: Simple and complex spike responses of mouse cerebellar Purkinje neurons to regular trains and omissions of somatosensory stimuli

Classification of Simple Spike Responses

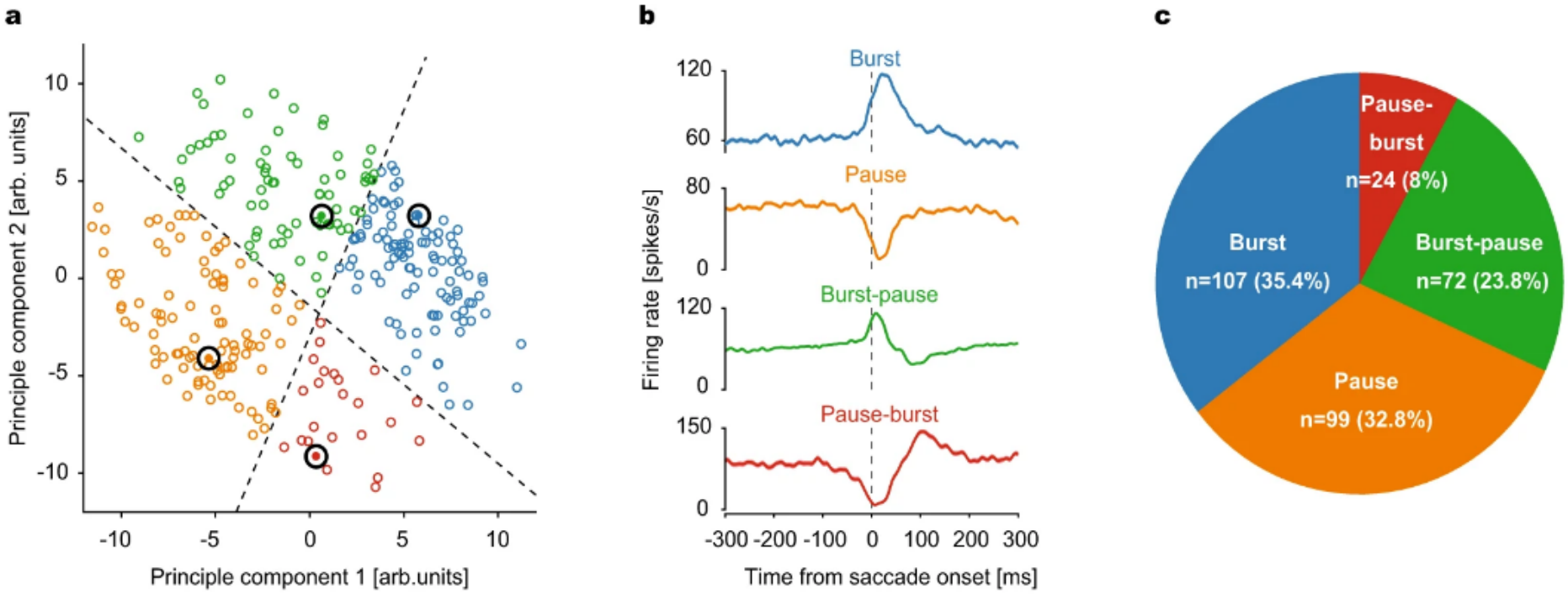


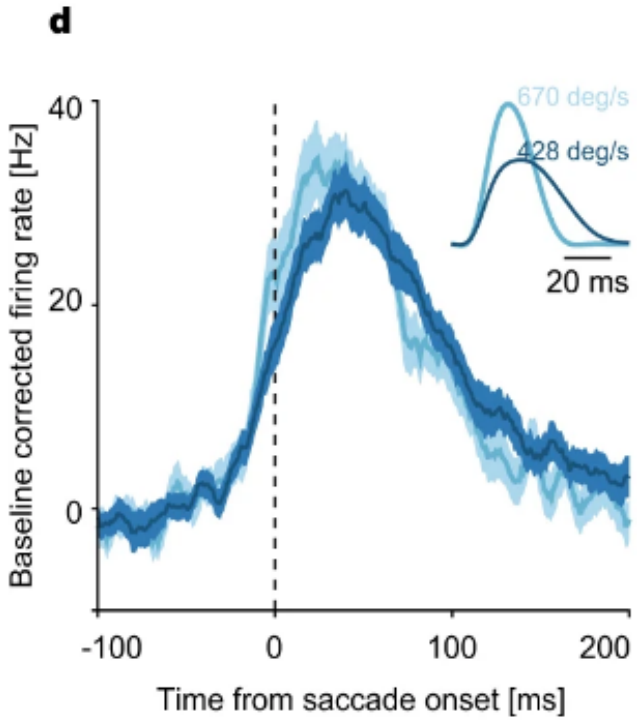
Figure: Classification of simple spike responses of Purkinje cells into different categories

Classification of Simple Spike Responses

- ⋆ **Burst:** Some PCs demonstrated a sharp peri-saccadic increase (or burst) in SS firing for saccades made in one direction, while exhibiting a sudden drop (or pause) in SS firing for saccades made in the opposite direction.
- ⋆ **Pause:** Other PCs exhibited a decrease (or pause) in SS firing during saccades made in one direction, while showing an increase (or burst) in SS firing for saccades made in the opposite direction.
- ⋆ **Burst-Pause and Pause-Burst:** Some PCs exhibited both types of changes, yet in opposite succession, during saccades made in different directions.

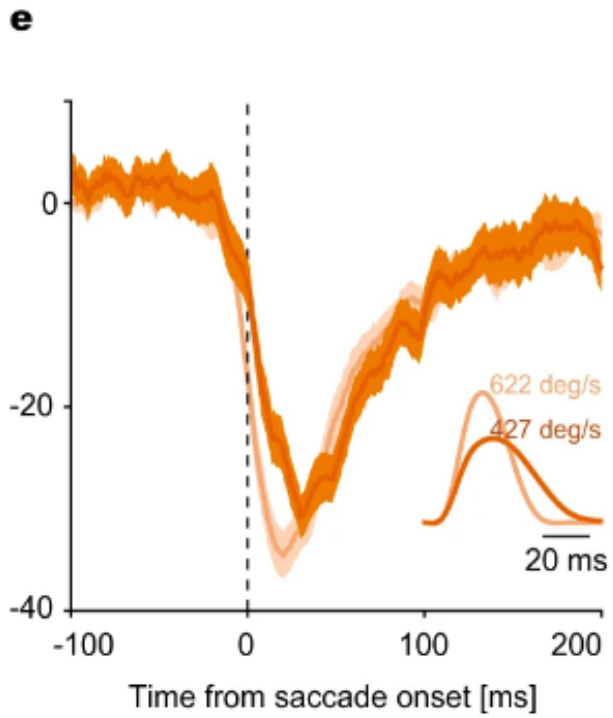
Burst

Some PCs demonstrated a sharp peri-saccadic increase (or burst) in SS firing for saccades made in one direction, while exhibiting a sudden drop (or pause) in SS firing for saccades made in the opposite direction.



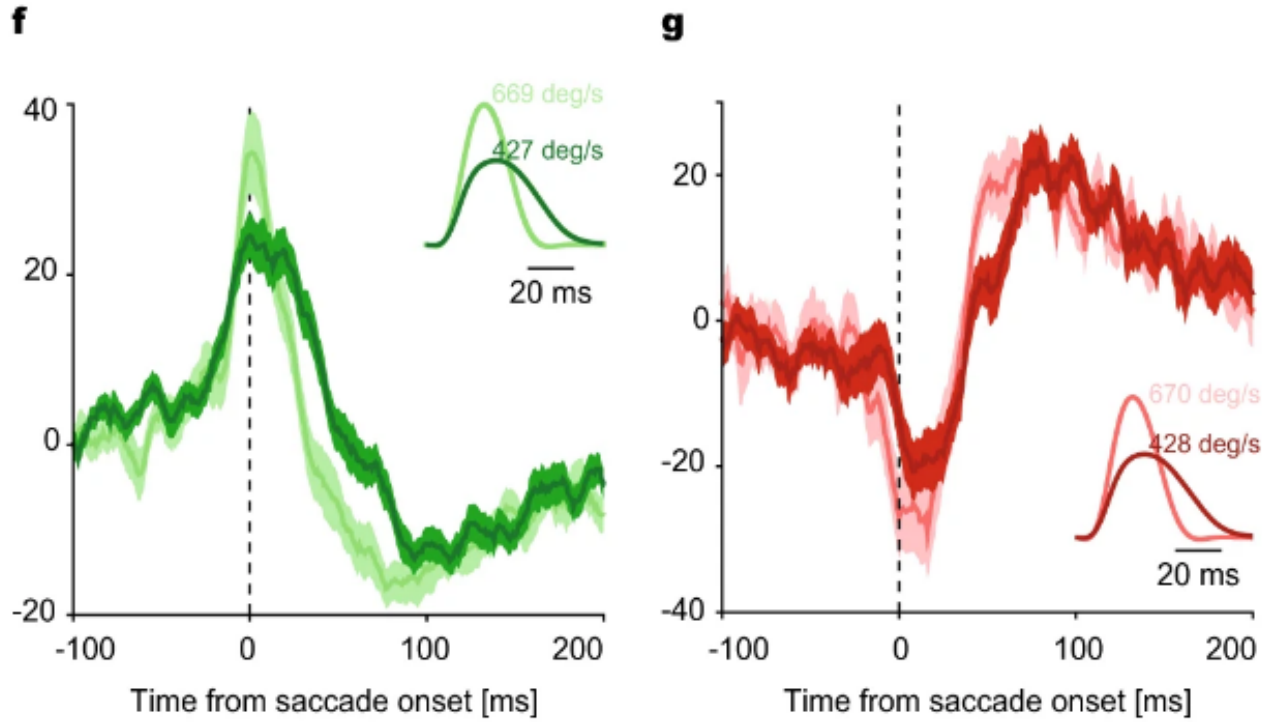
Pause

Other PCs exhibited a decrease (or pause) in SS firing during saccades made in one direction, while showing an increase (or burst) in SS firing for saccades made in the opposite direction.



Burst-Pause and Pause-Burst

Some PCs exhibited both types of changes, yet in opposite succession, during saccades made in different directions.



Linear Feed-Forward Network Model Shows High-dimensional Transformations by the Cerebellar Cortex

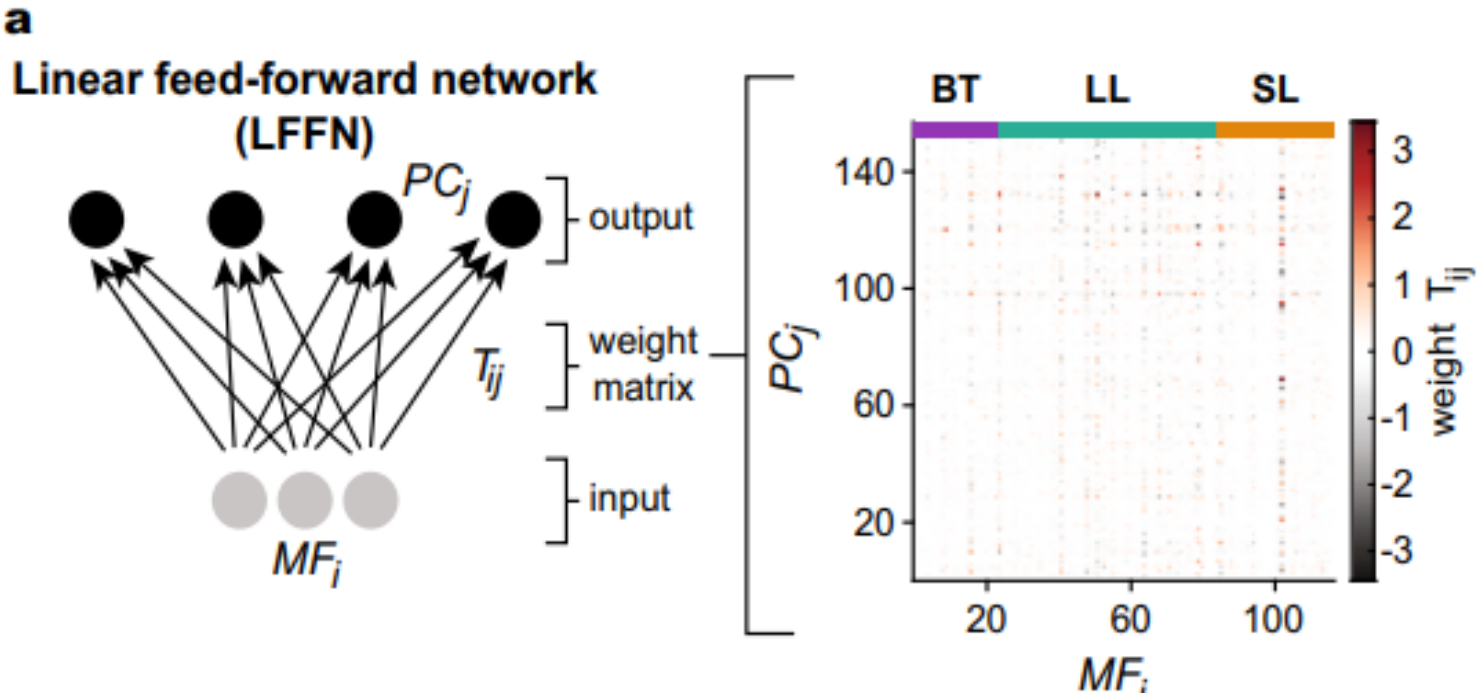


Figure: Schematic diagram showing LFFN for MF-to-PC firing rate transformation.

Rate Models for Individual MFs and PCs

The model incorporated a linear combination of kinematics-independent and kinematics-dependent components to estimate firing rates.

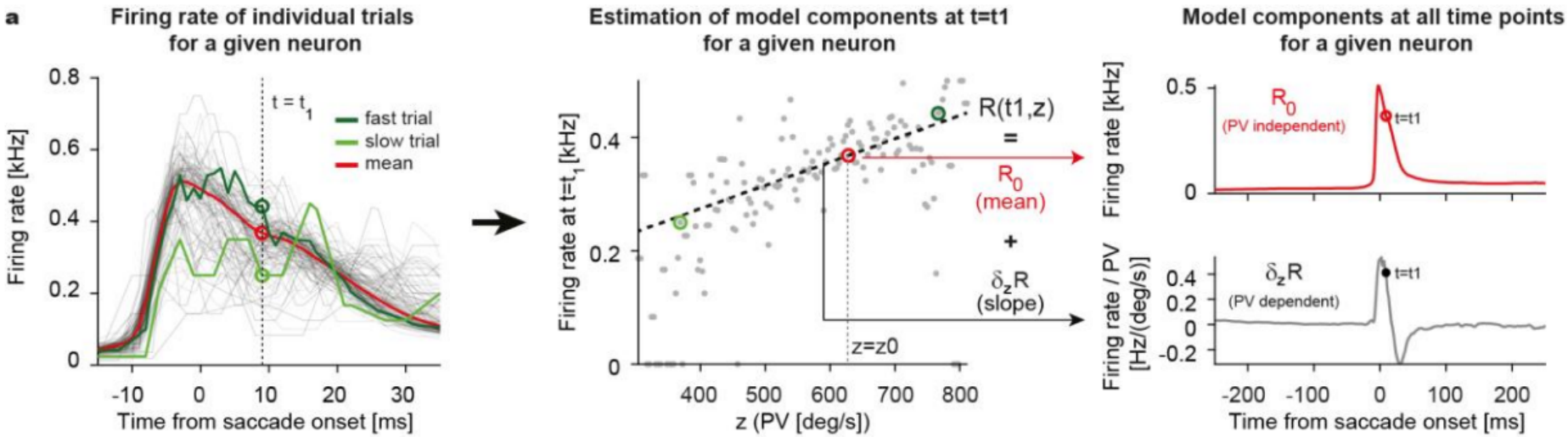
$$R(t;Z) = R_0(t) + R_Z(t)$$

$$R_Z(t) \approx \sum_{z \in Z} \delta_z R_z(t)$$

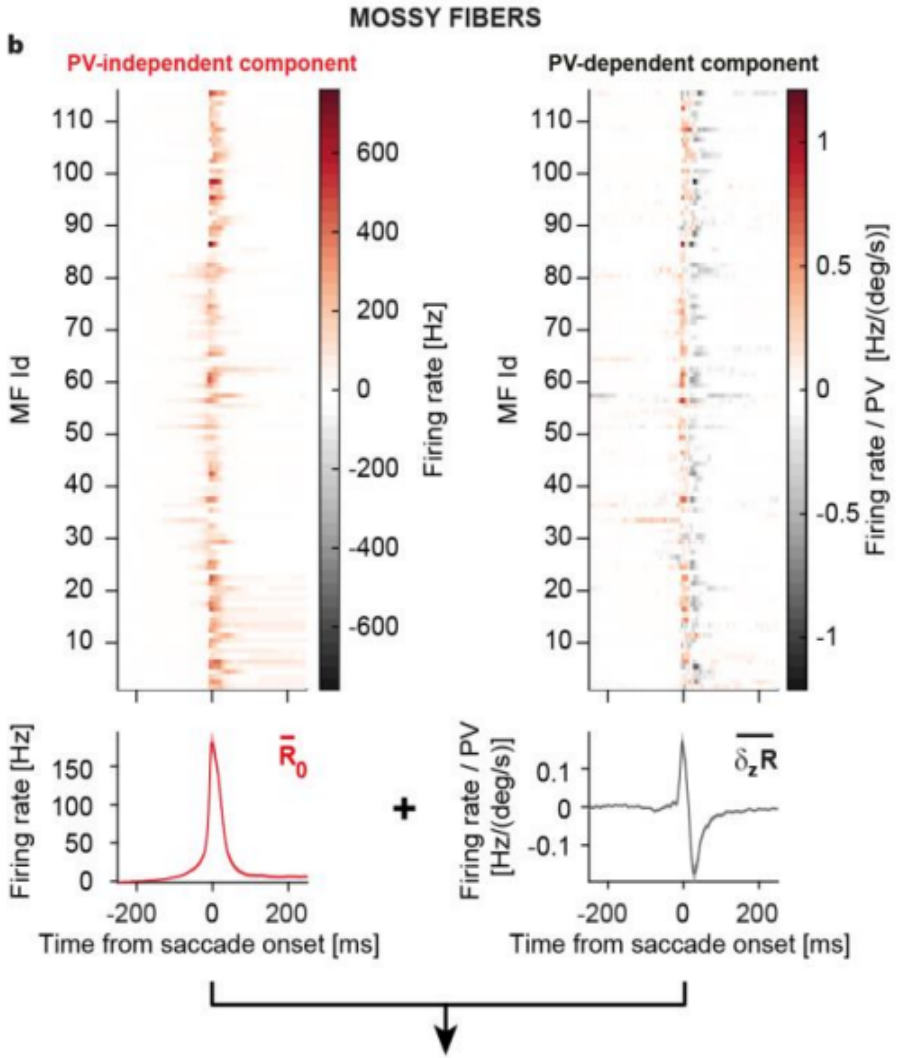
$$\Longrightarrow R(t;Z) \approx R_0(t) + \sum_{z \in Z} \delta_z R_z(t)$$

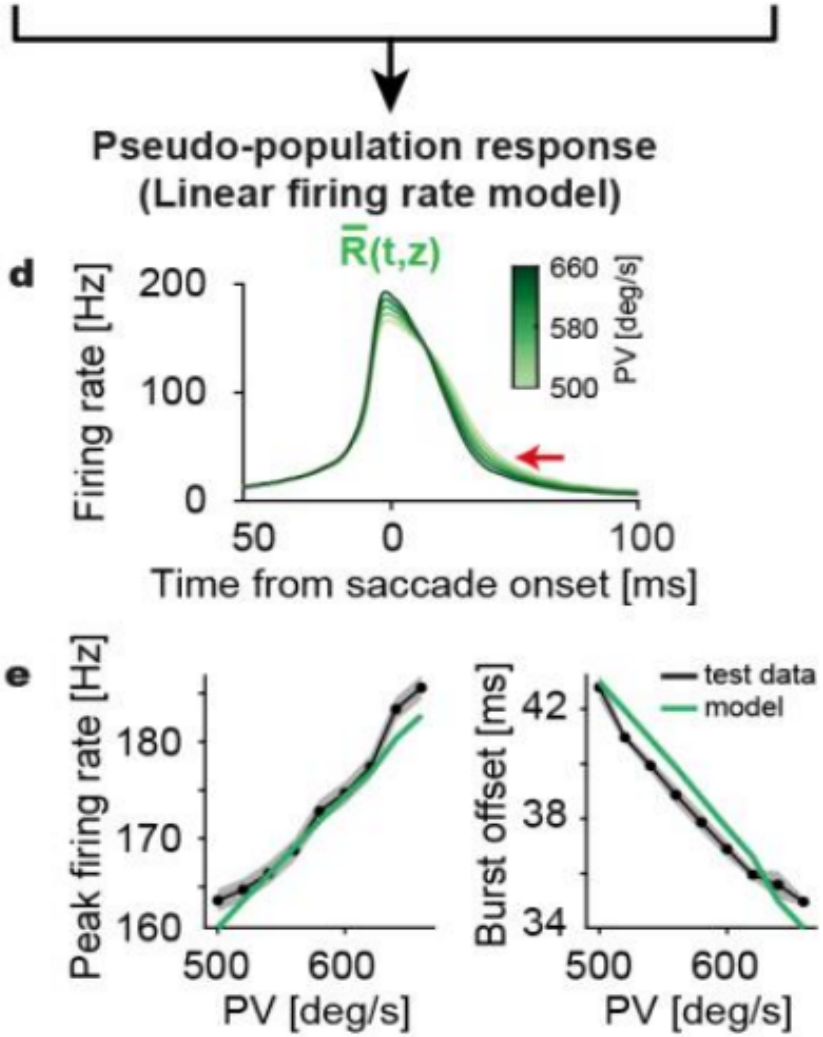
Z is a vector of the specific movement kinematic parameter
For example $Z =$[PV] or [duration] or a pair of kinematic parameters,
i.e., $Z =$ [PV, duration].

Rate Model Example



Testing the Model





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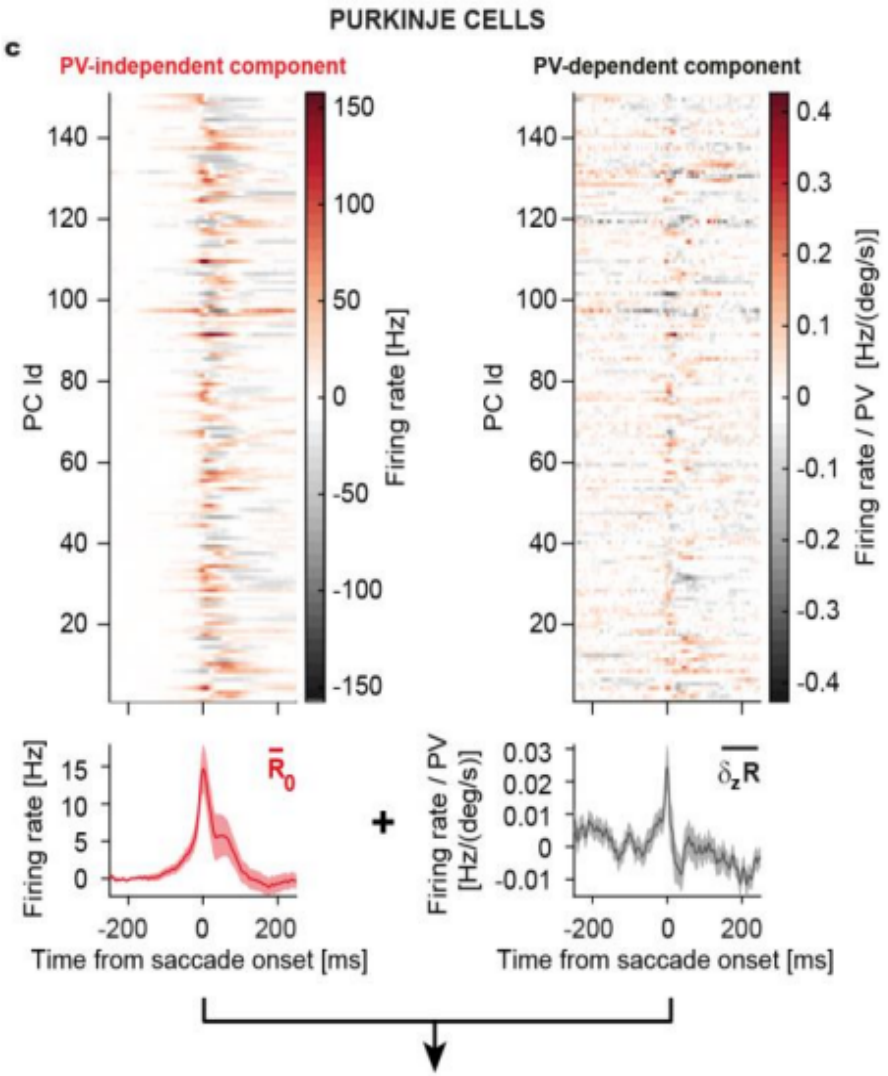
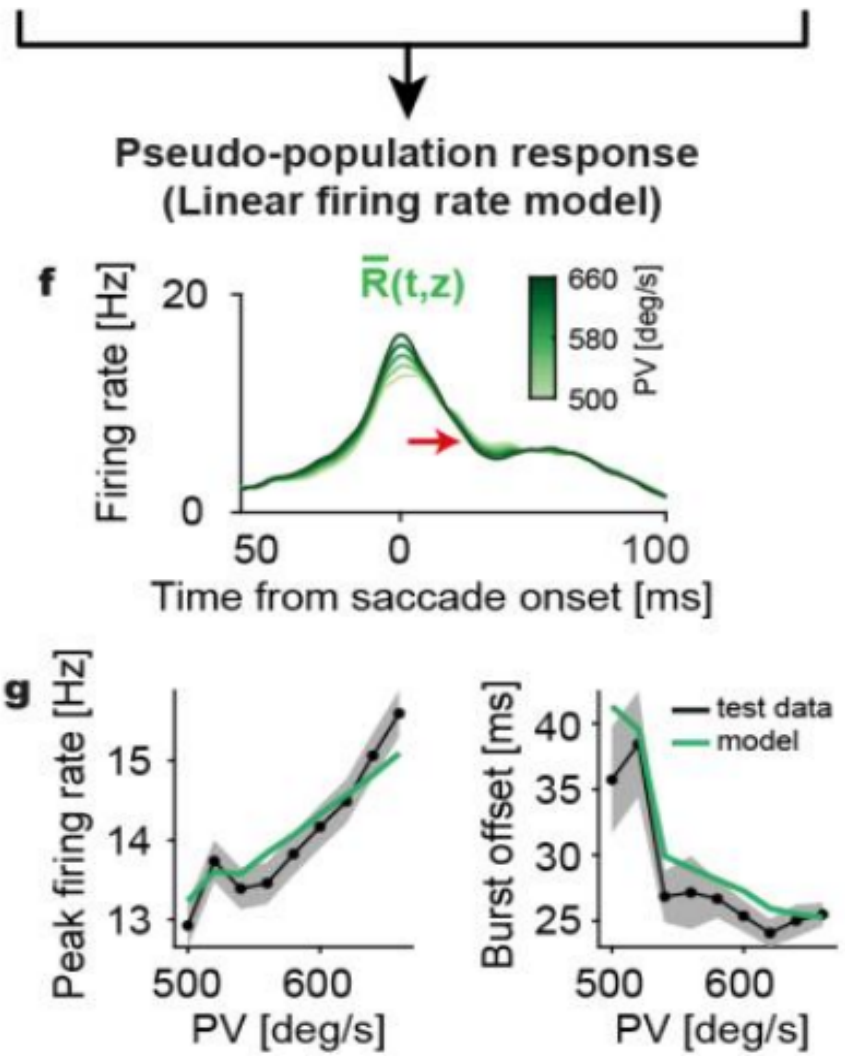
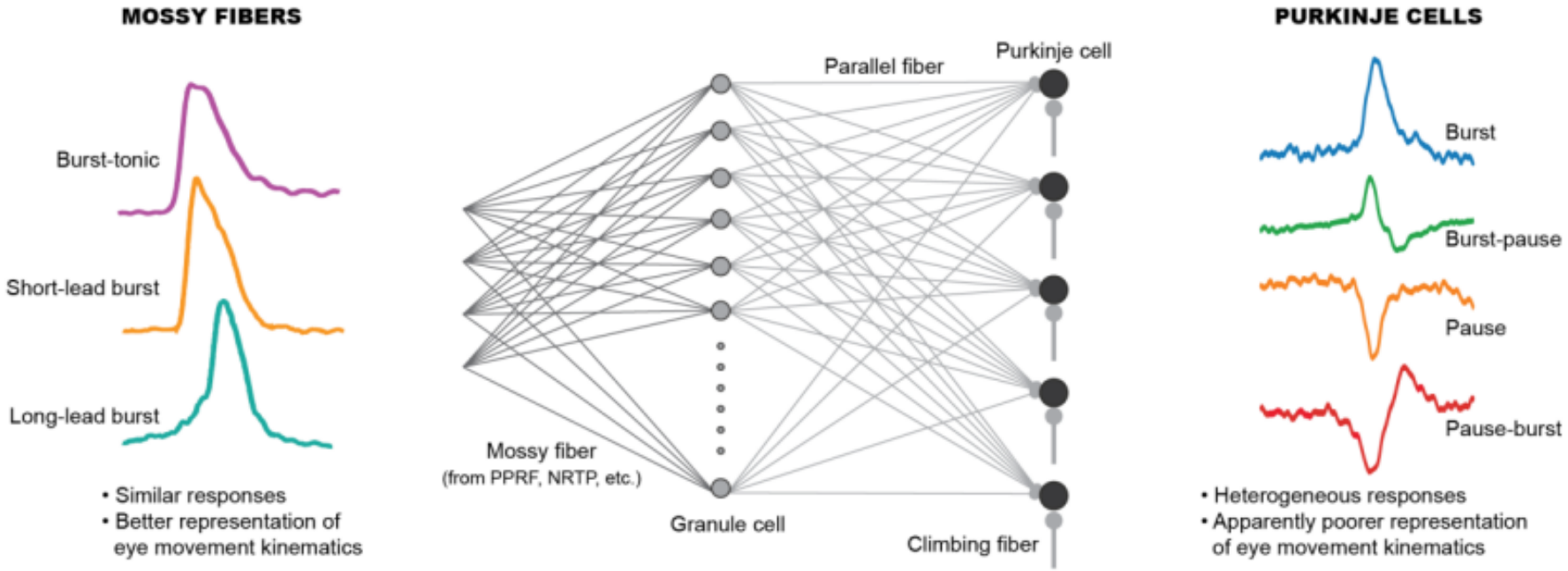
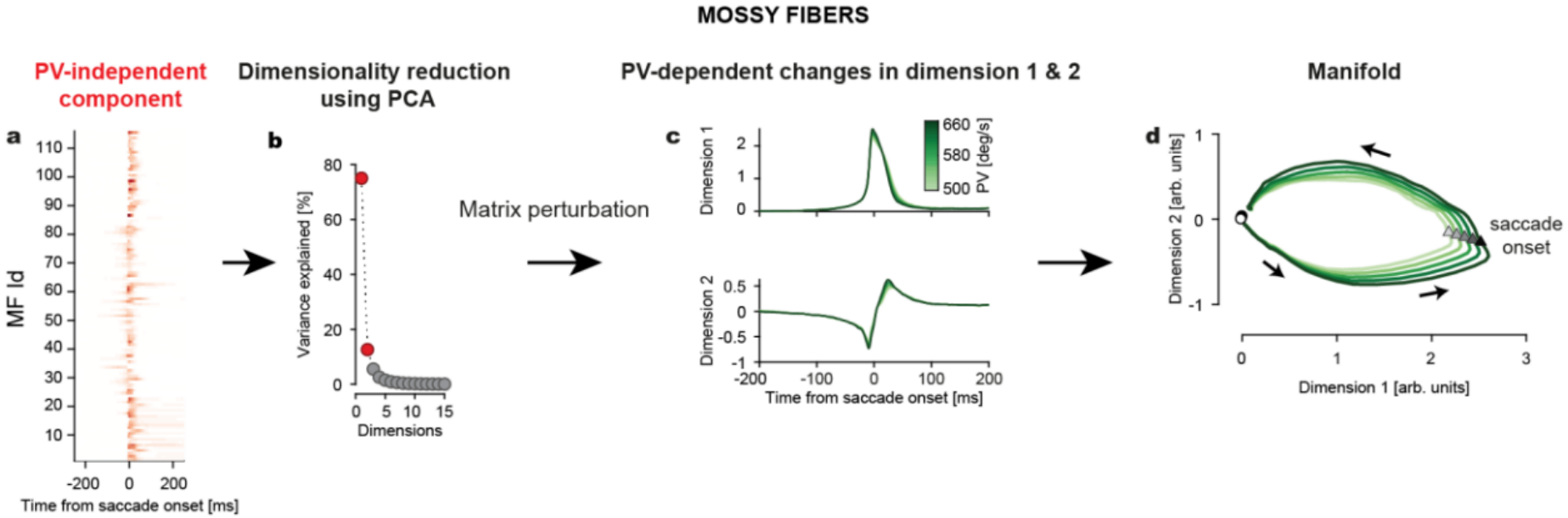




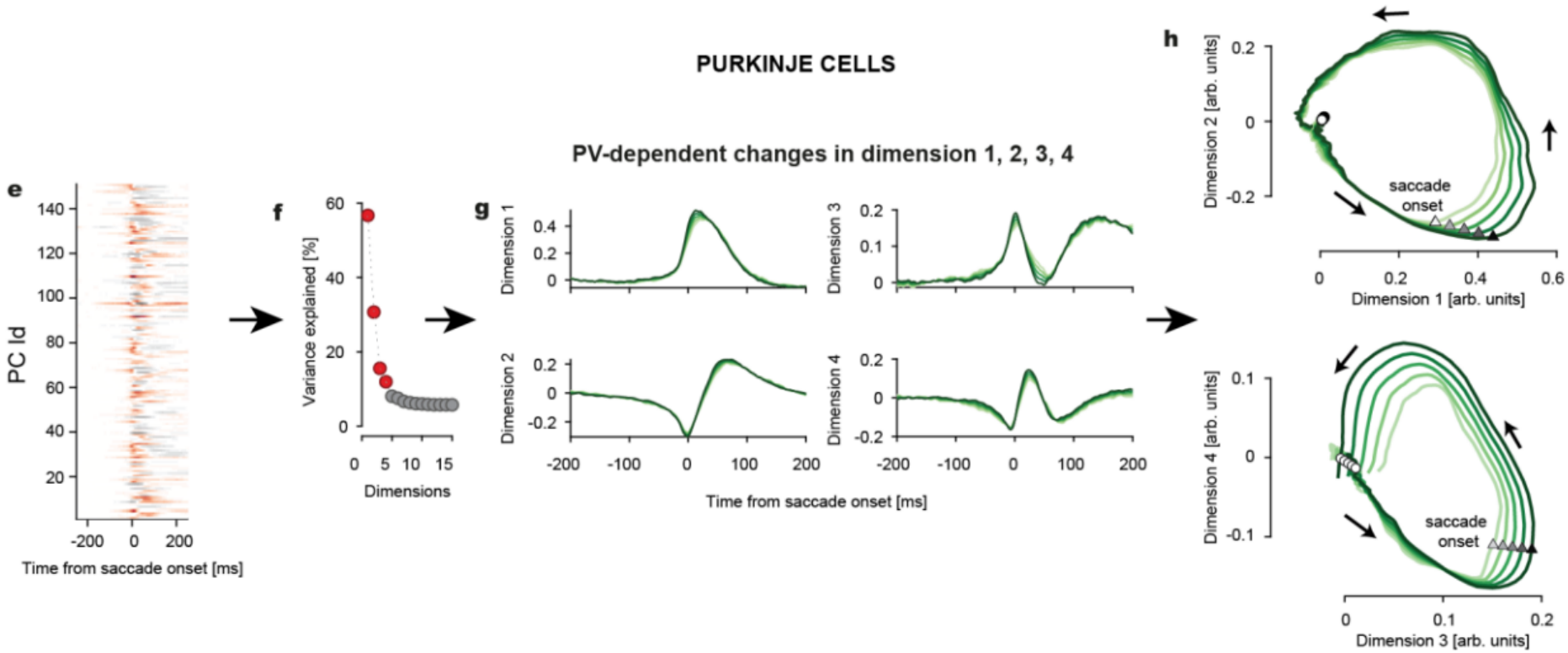
Linear Feed-Forward Network Models (LFFN)



Estimation of Manifolds - MFs



Estimation of Manifolds - PCs



Data Source & Codes

All source data files are provided with this paper and can be downloaded from https://doi.org/10.5281/zenodo.7732421. Source data are provided in the paper.

All underlying codes to reproduce the results and figures of the paper are available at https://doi.org/10.5281/zenodo.7732421.

Thank you!