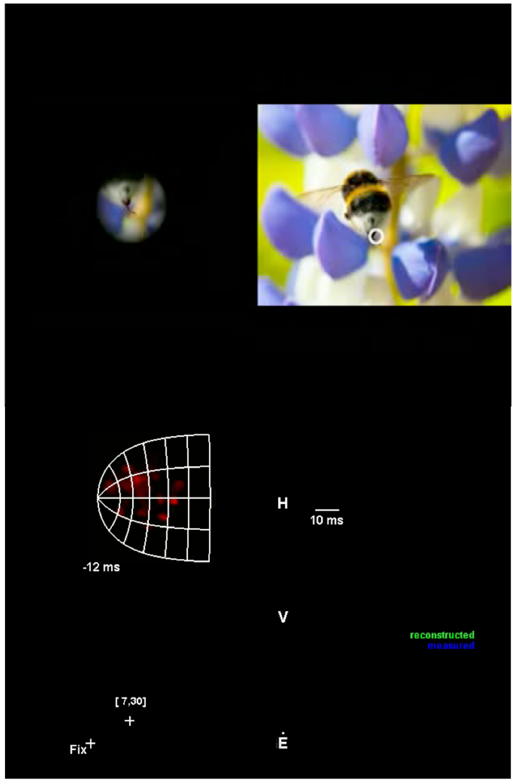
Human and robotic eye-head

3D gaze control

in a multisensory world:

Lisboa-Nijmegen ERC project "Orient"



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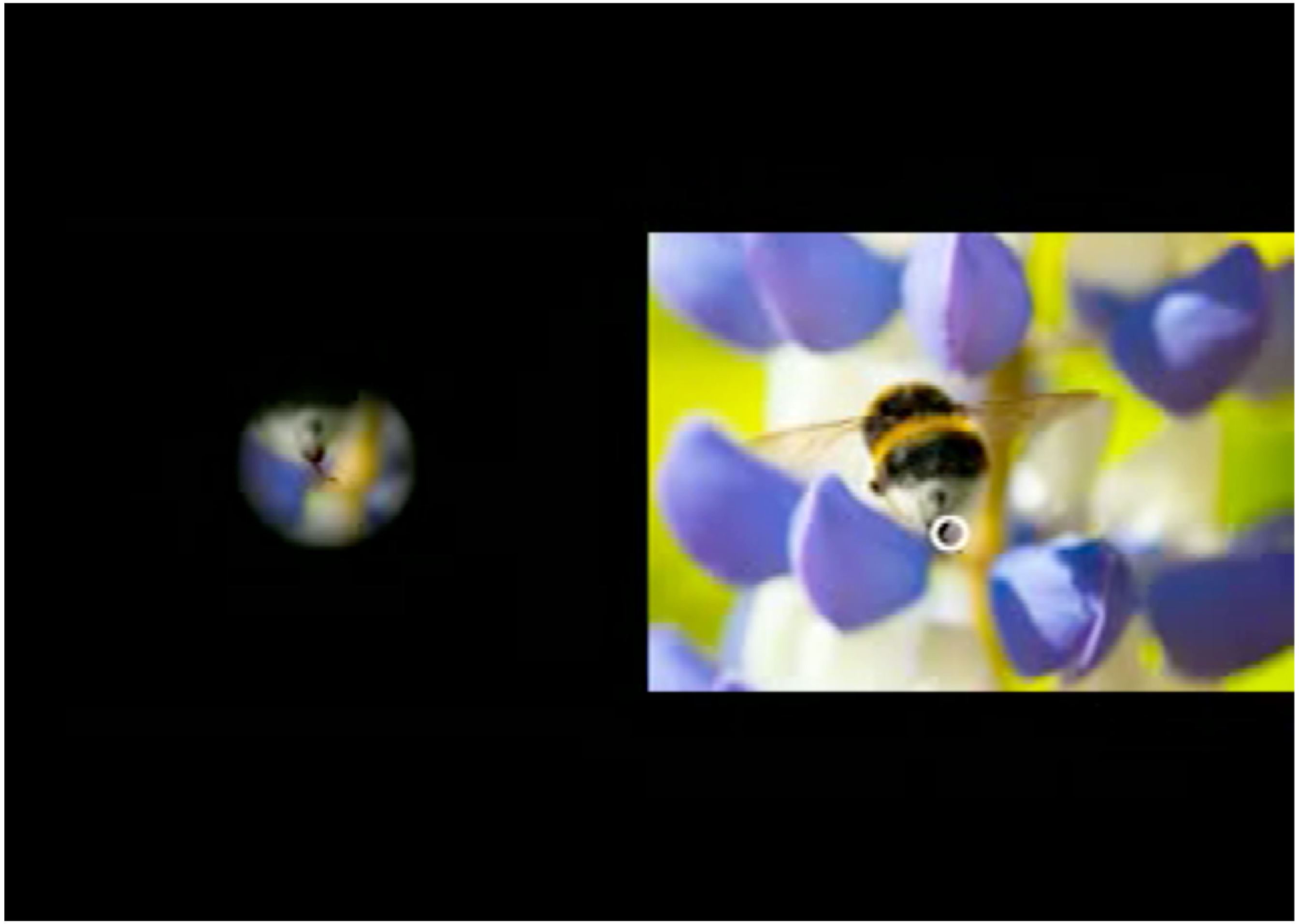
Saccades: Why?

WHAT YOU SEE **WHAT YOU GET**



High-resolution, discontinuous local (foveal) input

A high-resolution global, stable percept

We make ~3 saccades/s;
For each saccade, the brain should decide:

- **What?**
- **Where?**
- **When?**
- **How?**

To construct a stable visual representation, the saccadic system should account for its own behavior (efference copies/internal models/ memory/coordinate transformations).

Because of the low-resolution (uncertain) retinal periphery, the gaze-control system is thought to optimize **speed-accuracy trade-off**.

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The saccadic gaze-control system is a “clever” system, optimally organized to carry out a well-defined task:

“DIRECT THE FOVEA AS FAST AND AS ACCURATELY AS POSSIBLE TO THE TARGET”

However, the system has to overcome several nontrivial problems:

1) Deal with a sluggish (overdamped) oculomotor plant
2) Deal with costs of overshoots and sensorimotor noise
3) Deal with spatial-temporal uncertainties in peripheral vision
4) Update target coordinates after every intervening movement
5) Coordinate eyes and head in different reference frames
6) Account for the non-commutative properties of 3D rotations

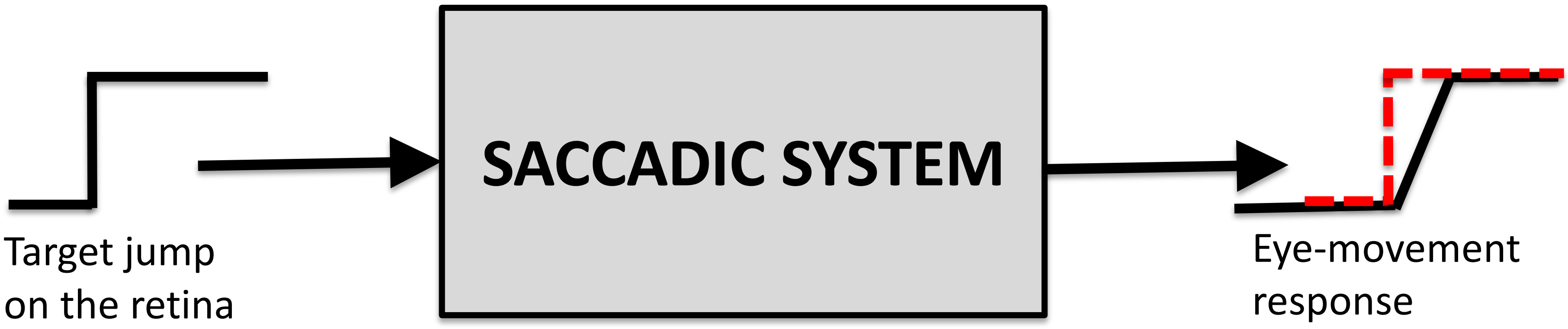
1

How to overcome a sluggish oculomotor plant?

1. Saccades: How?

First, some Linear System's theory:

We consider a saccadic eye movement as the
STEP POSITION RESPONSE of the visuomotor system.



Let's suppose that an ideal saccade = **a STEP**

An optimal saccadic system should then perform the **IDENTITY OPERATION (output = input)**.

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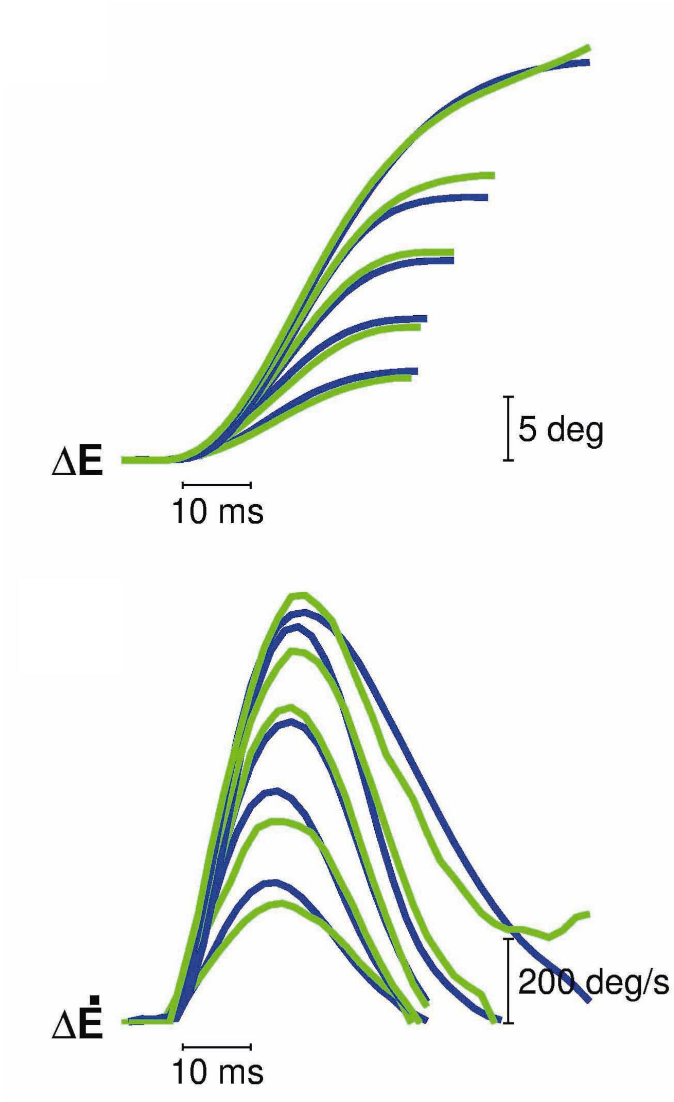
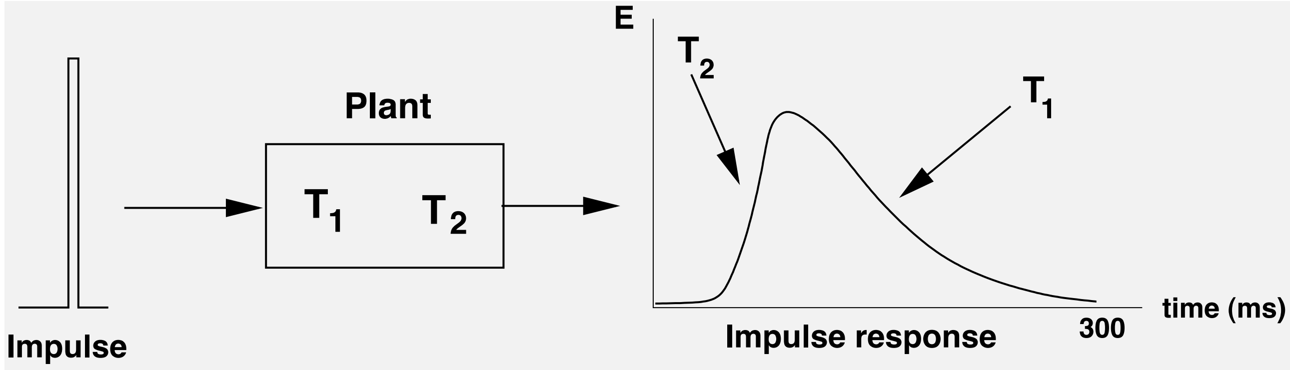
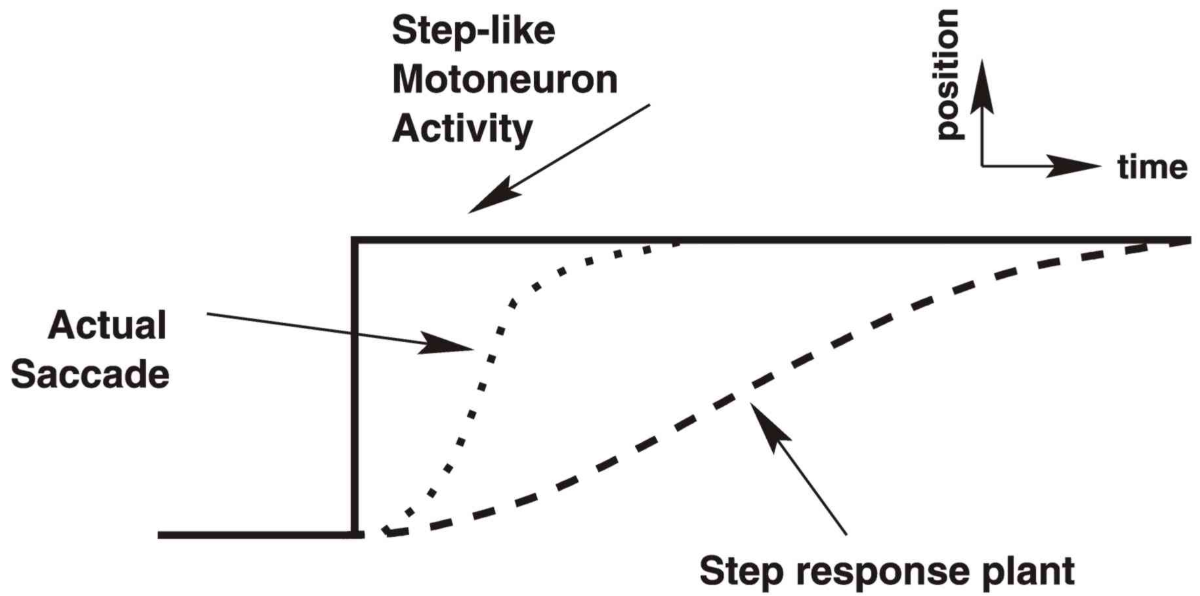
1. Saccades: How?

However, the eye/muscles/tissues behave as an **overdamped plant**







Conclusion, the motor-neuronal control signal CANNOT be a position-step command!

1. Saccades: How?

With a (linear) model of the plant its control signal can be readily predicted.
Dave Robinson modeled the plant transfer function by two Voigt elements in series:

$$? \rightarrow \boxed{H(s) = \frac{1 + sT_z}{(1 + sT_1)\cdot(1 + sT_2)}} \rightarrow$$

1/s

IN: M(s) **H(s)** **OUT: E(s)**

Linear Systems Theory: $E(s) = H(s) \cdot M(s)$

[$c = f(T_1, T_2, T_z)$]

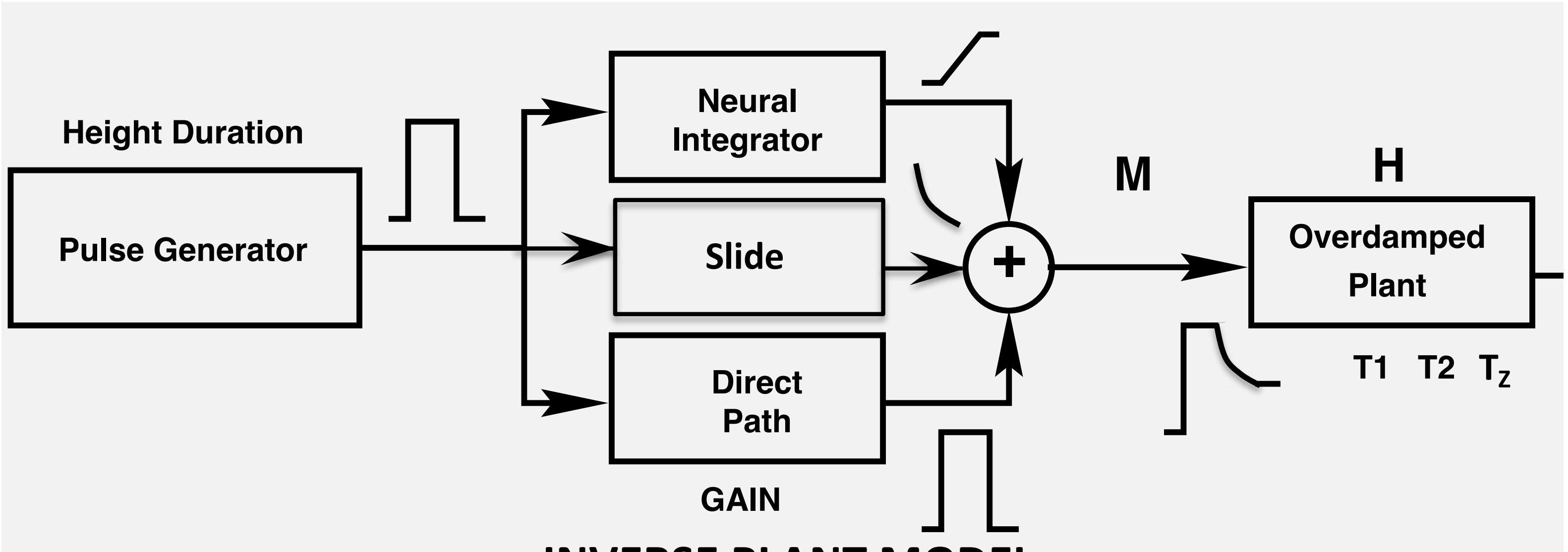
$$M(s) = \frac{E(s)}{H(s)} \Rightarrow M(s) = \frac{T_1 T_2}{T_z} + \frac{1}{s} + \frac{c}{s + 1/T_z}$$

1. Saccades: How?

$$M(s) = \frac{T_1 T_2}{T_z} + \frac{1}{s} + \frac{c}{s + 1/T_z} \Rightarrow m(t) = \frac{T_1 T_2}{T_z}\delta(t) + U(t) + c \cdot \exp(-t/T_z)$$

This plant model thus predicts that the optimal motorneuron control contains THREE signals:

- a PULSE (height T_1T_2/T_z): $\delta(t)$
- a STEP: $U(t)$
- an exponential SLIDE (T_z): $\exp(-t/T_z)$



INVERSE PLANT MODEL
(PULSE-SLIDE-STEP GENERATOR, or PSSG)

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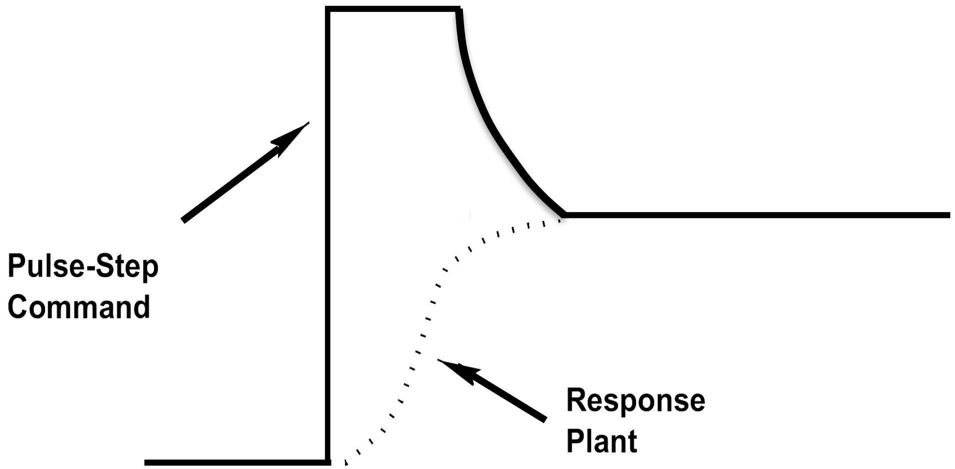
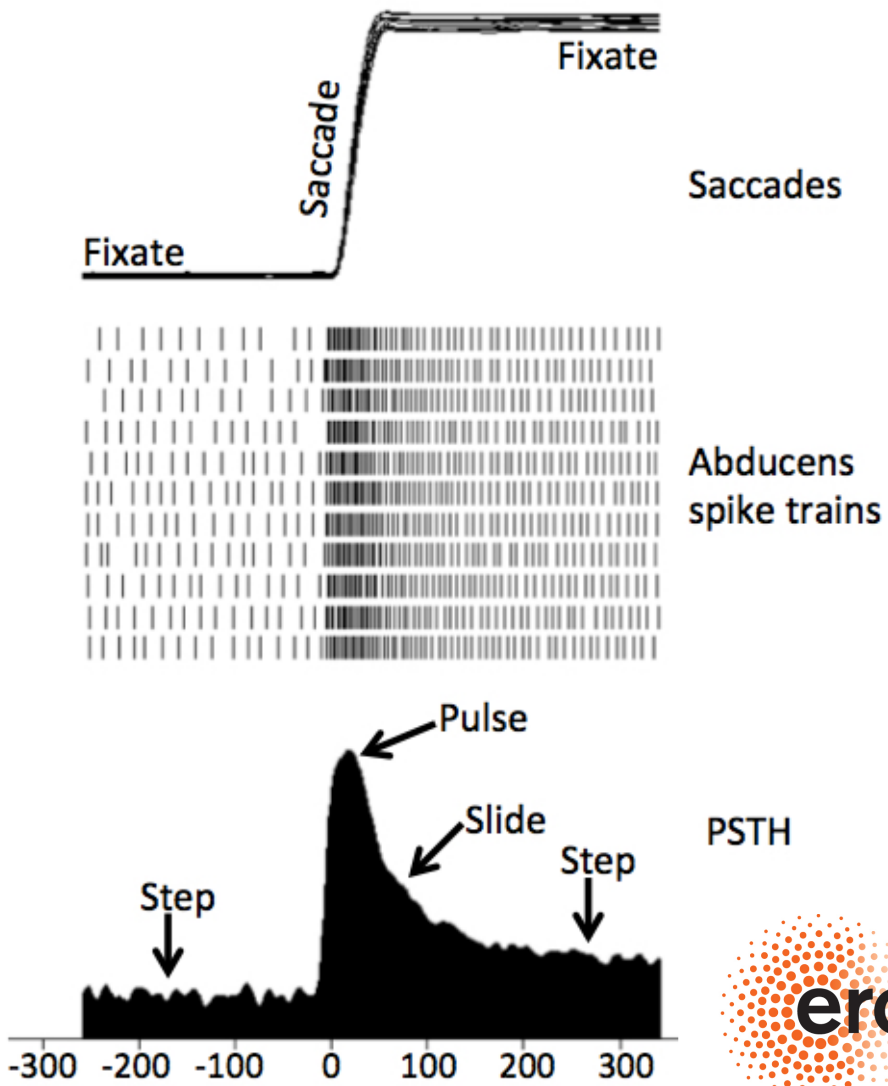
1. Saccades: How?

From the simple linear, overdamped, model for the eye plant (muscles + globe) the theoretical prediction is that the optimal neural control signal is a **PULSE-SLIDE-STEP** motor command!
This prediction has been verified by neural recordings from oculomotor neurons.





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2

Saccade Kinematics: nonlinear main sequence

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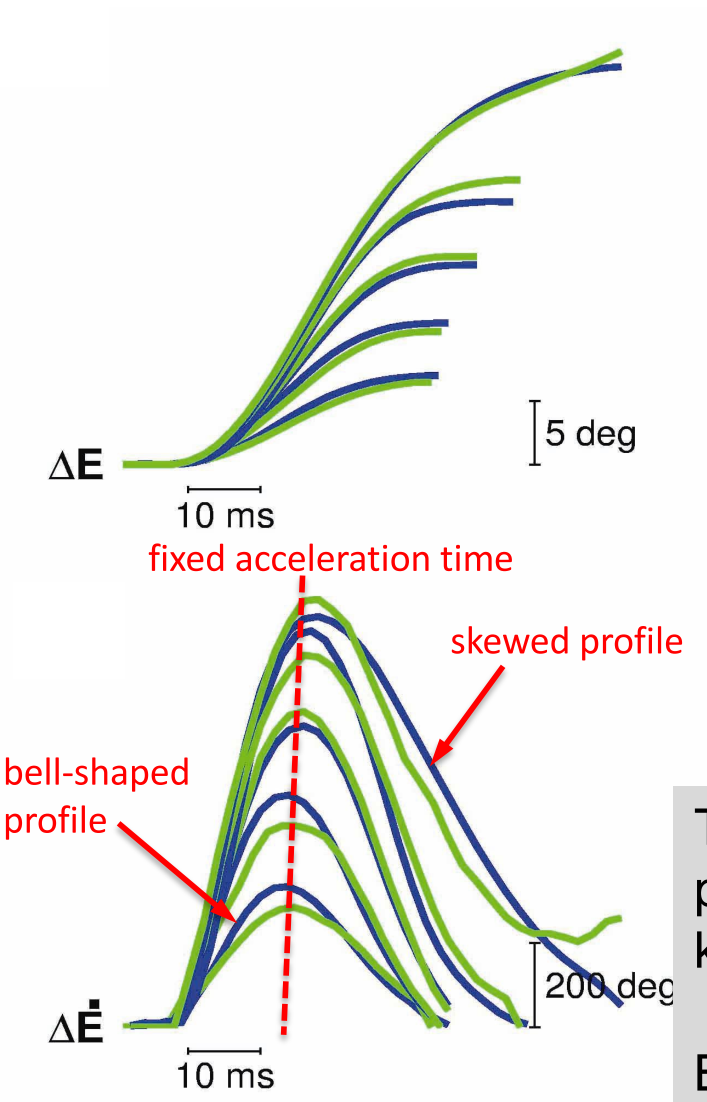
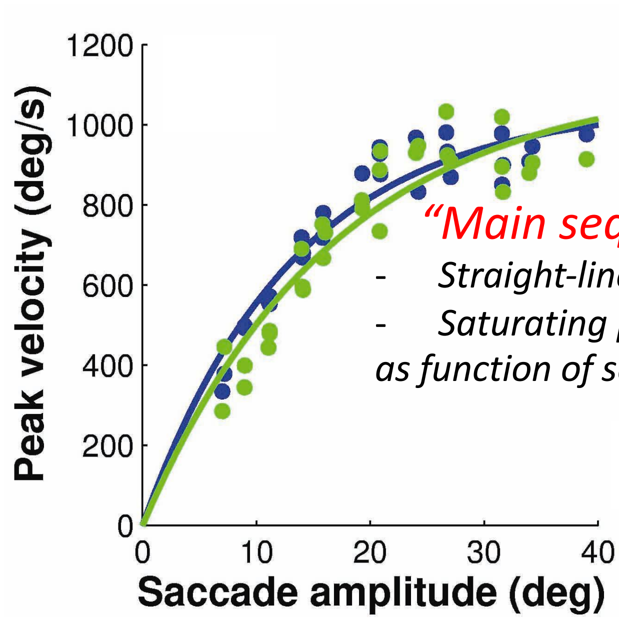
2. Saccades: kinematics

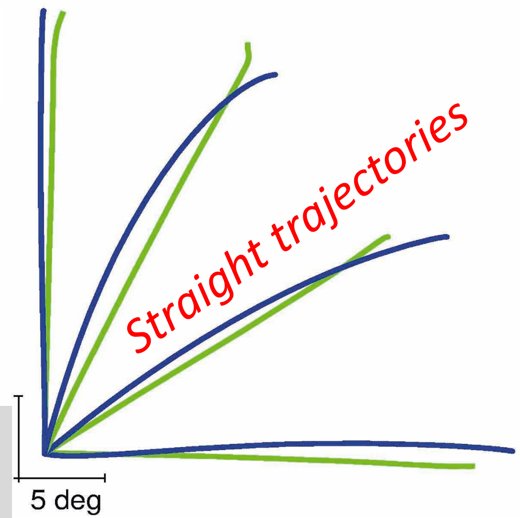




"Main sequence:"

- *Straight-line increase of saccade duration*
- *Saturating peak eye velocity*

as function of saccade amplitude



The PULSE contains all the properties seen in the saccade kinematics (velocity profiles).

Because of the main sequence the saccadic pulse controller must be **nonlinear**!

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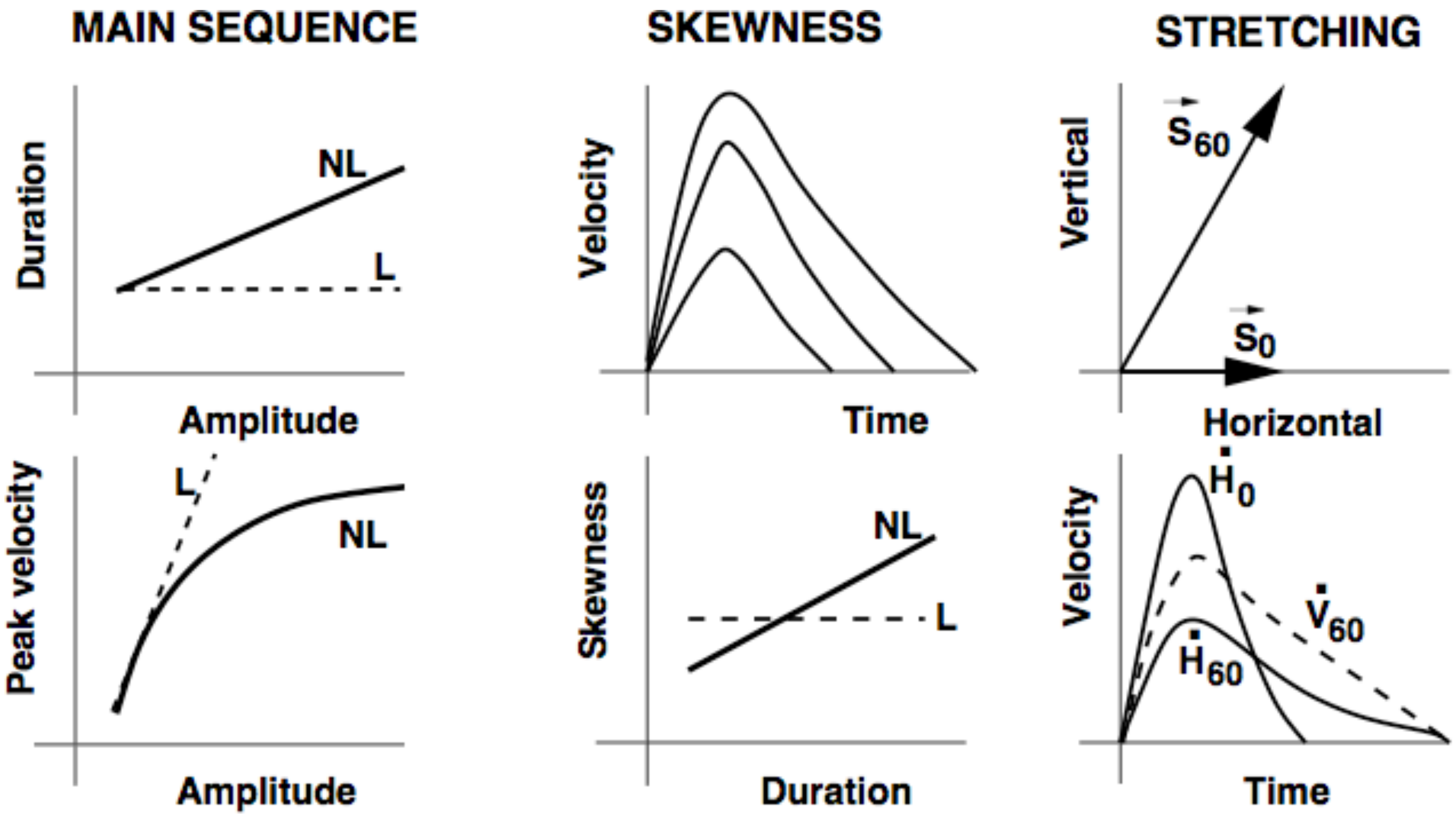
2. Saccades: nonlinear kinematics



- **Main sequence**: the stereotyped relation between amplitude, duration and peak velocity betray a **nonlinearity** in the system
- **Skewness** of velocity profiles increases with saccade duration
- Oblique saccades are straight because of **component stretching**

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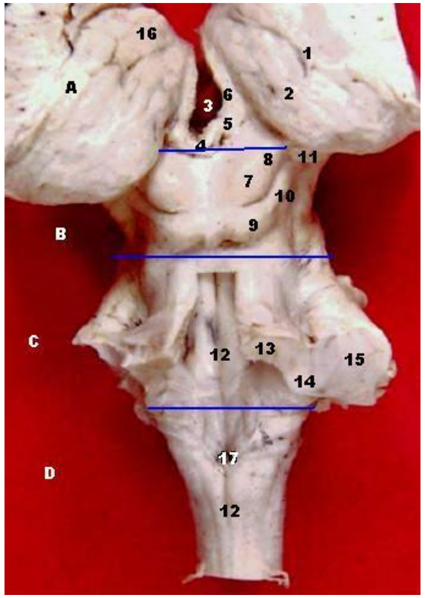
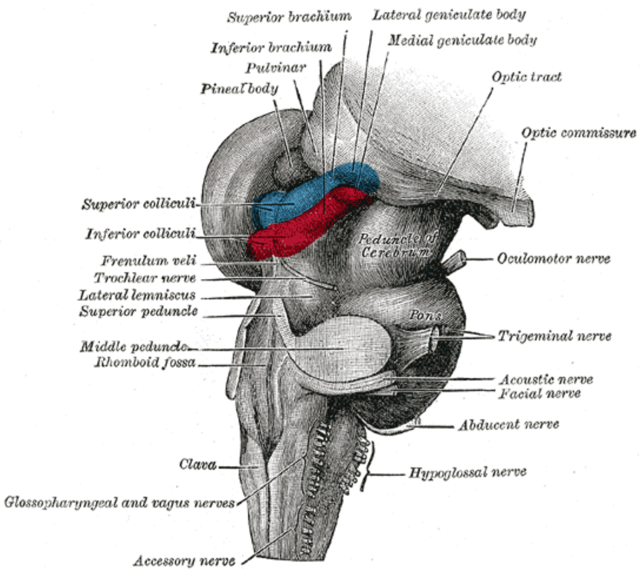
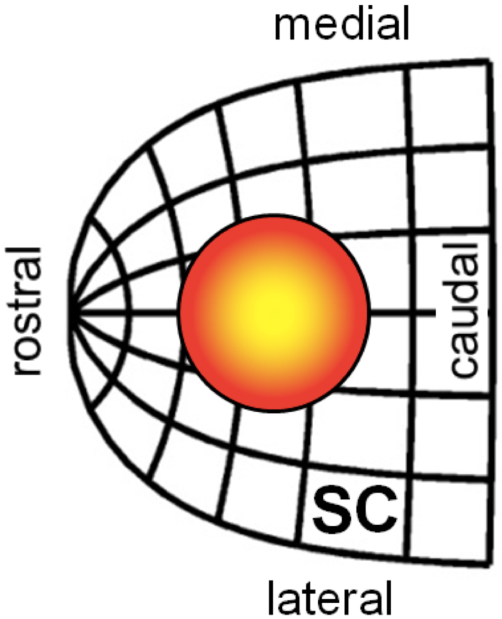
2. Saccades: nonlinear kinematics







∃ Saccadic gaze-motor map in the SC, in which a local population encodes the eye-head saccade.

- Recent theoretical studies suggest that the nonlinear main-sequence relations reflect a **deliberate strategy** to **optimize speed-accuracy trade-off** in the presence of **signal-dependent noise**

- The **midbrain Superior Colliculus** is in an **ideal position** to **implement** such an **optimal control principle** because it is a key sensory-motor interface for saccades

- **Previous findings from my lab**: main-sequence properties of saccades are indeed reflected in the spatial-temporal activity patterns of the SC.

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HOW?

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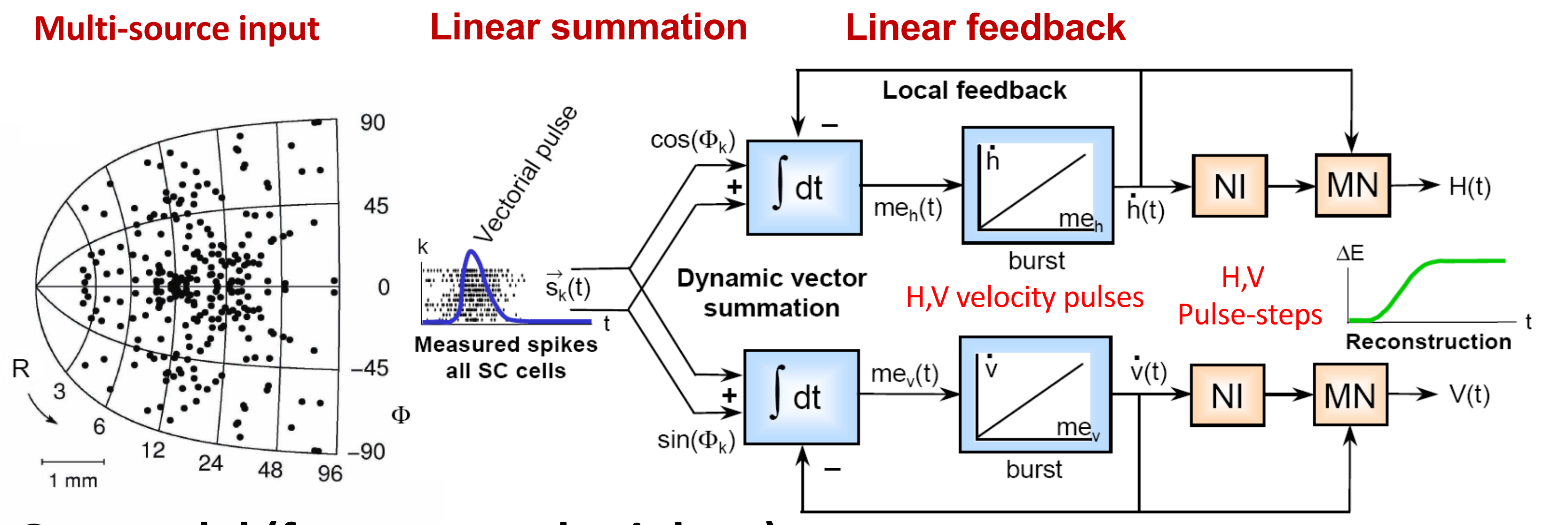
2. SC motor map is a nonlinear, vectorial pulse generator



Our model (from neurophysiology):

- Each spike from each SC neuron adds an infinitesimal, site-specific, **'2D spike-vector'** contribution to the eye motor command: $\vec{m}_k = [x(u_k, v_k),\ y(u_k, v_k)]$

- The **intended trajectory** is determined by dynamic **linear vector summation** of all spike vectors:
$$\vec{s}_k(t) = \int_0^t \vec{m}_k \cdot \delta(t-\sigma)d\sigma \;\Rightarrow\; \vec{S}(t) = \sum_{k=1}^{POP} \vec{s}_k(t)$$

- We assume **linear feedback circuits** in the brain stem, in which horizontal and vertical **pulse generators are independent**

- Model (only **two free parameters, [B,ΔT]**) is applied to **measured SC activity** patterns (150 cells) for saccades in all directions.

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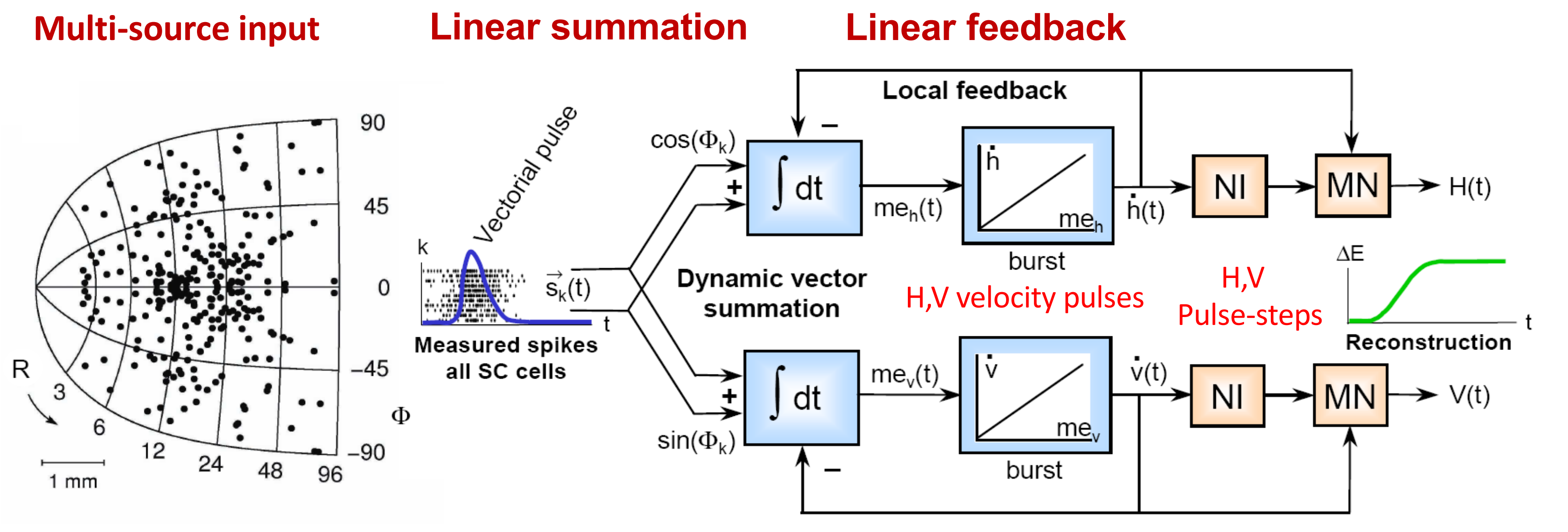
2. SC motor map is a nonlinear, vectorial pulse generator



$$E_{H,V}(s) = \frac{B \cdot SC(s)}{s \cdot \left(s + B \cdot e^{-s \cdot \Delta T}\right)}$$

The SC output – to – Eye-position output characteristic

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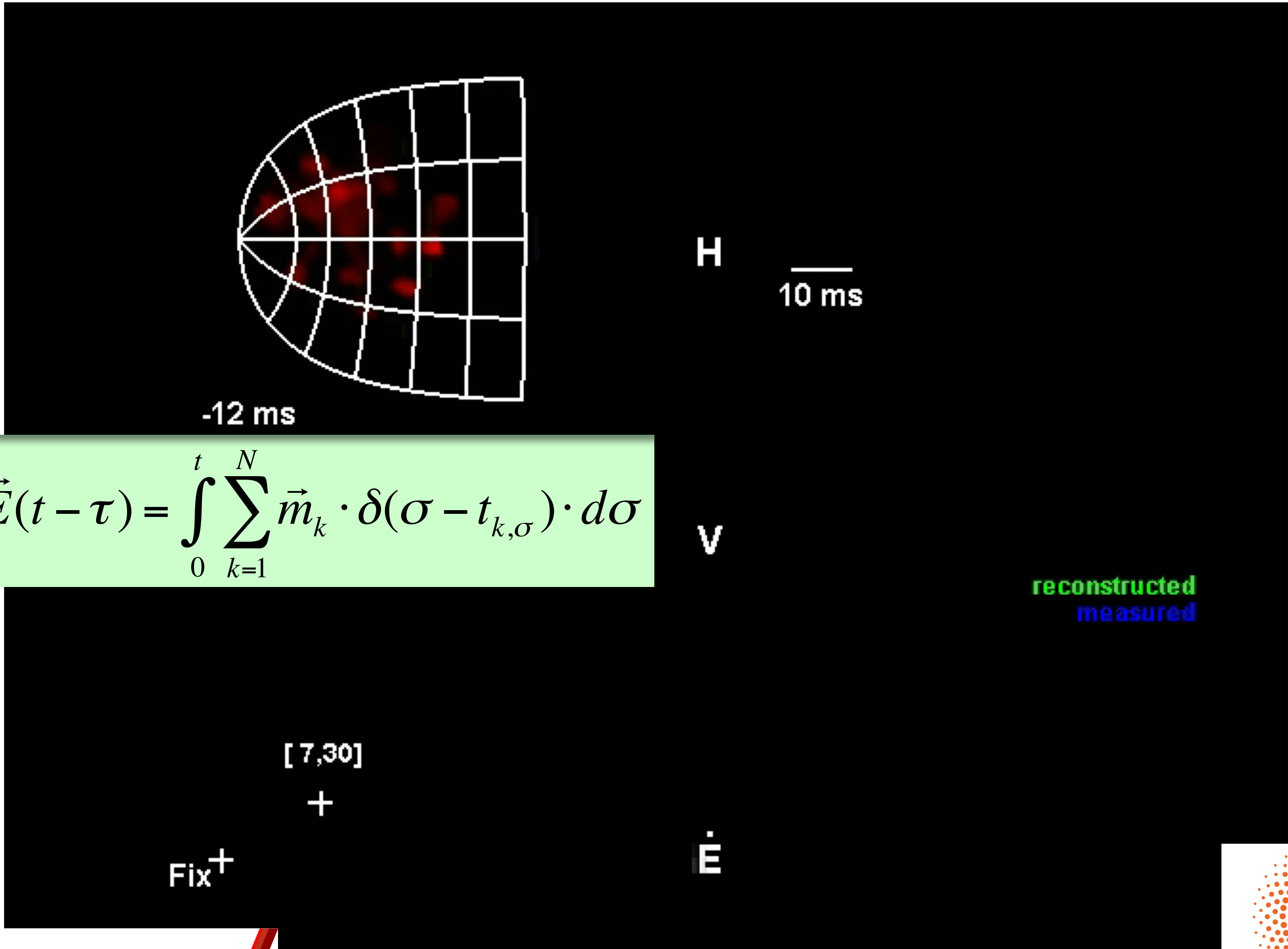
2. SC activity encodes the full saccade trajectory and kinematics



$$\Delta\vec{E}(t-\tau)=\int_0^t\sum_{k=1}^{N}\vec{m}_k\cdot\delta(\sigma-t_{k,\sigma})\cdot d\sigma$$

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3. 3D Rotational kinematics: How?

3

The eye is a rotating sphere, with 3 degrees of freedom.
How to deal with the noncommutativity of 3D rotations?

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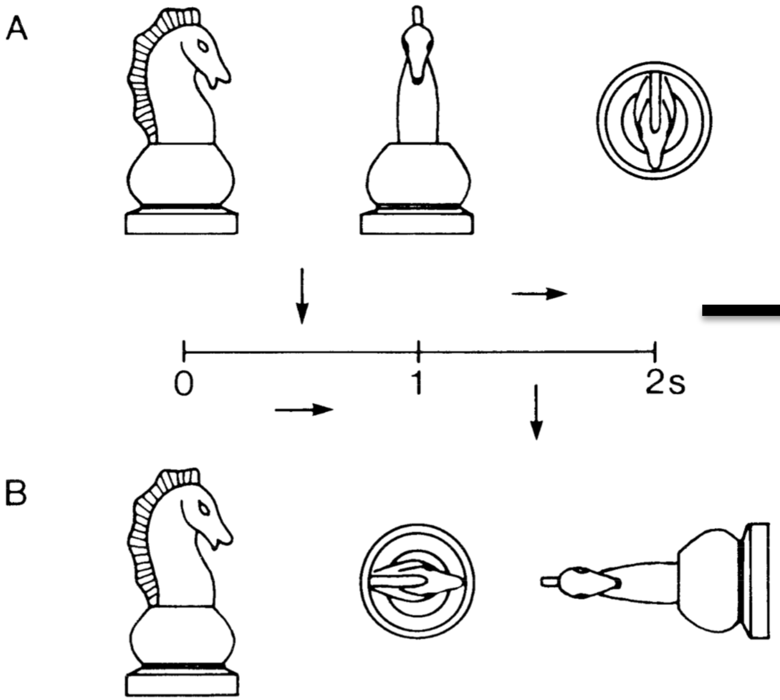
3. 3D Eye-movement kinematics

Rotations do not commute: $R_1R_2 \neq R_2R_1$

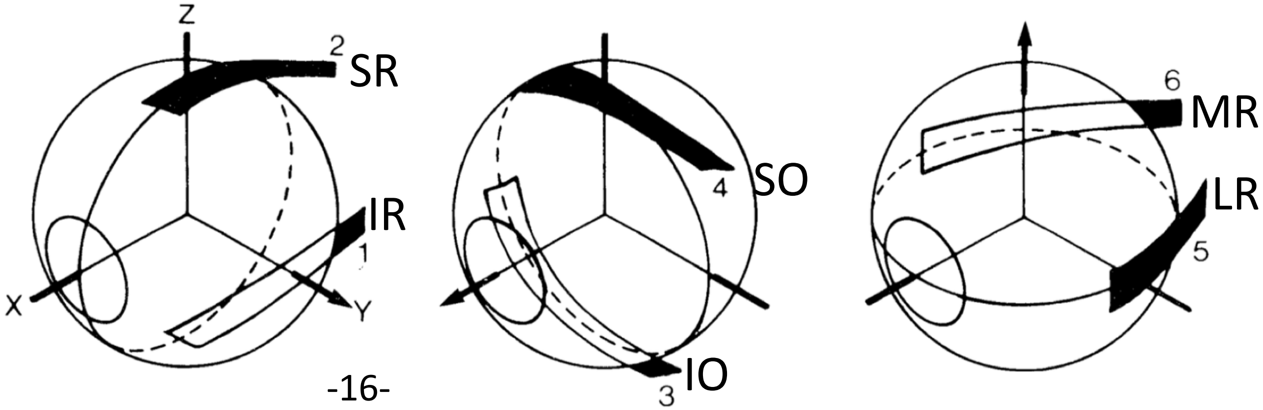


90 deg right rotation about the vertical axis

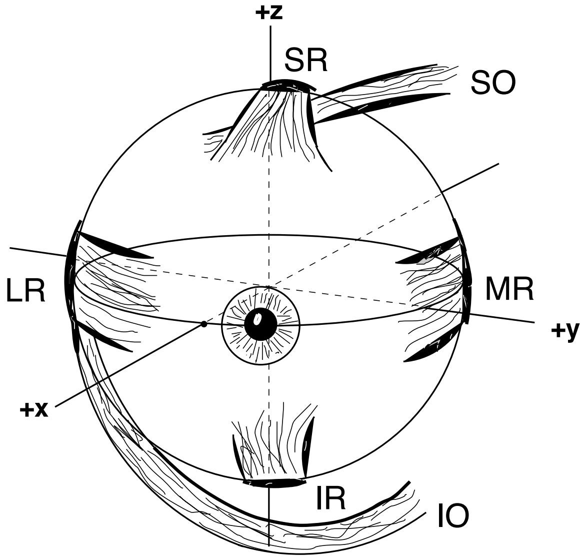
90 deg down rotation about the horizontal axis

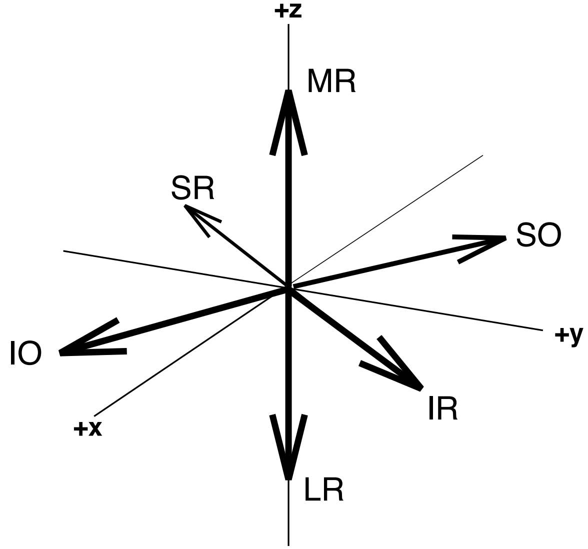
Consequences for saccades:

- For eye-movement sequences (N.B.: we make 3 saccades/s, i.e. >200,000/day), the order of these rotations would determine the final orientation of the eye!
- *This would lead to an accumulation of ocular torsion!*



3. Eye-movement kinematics in 3D:



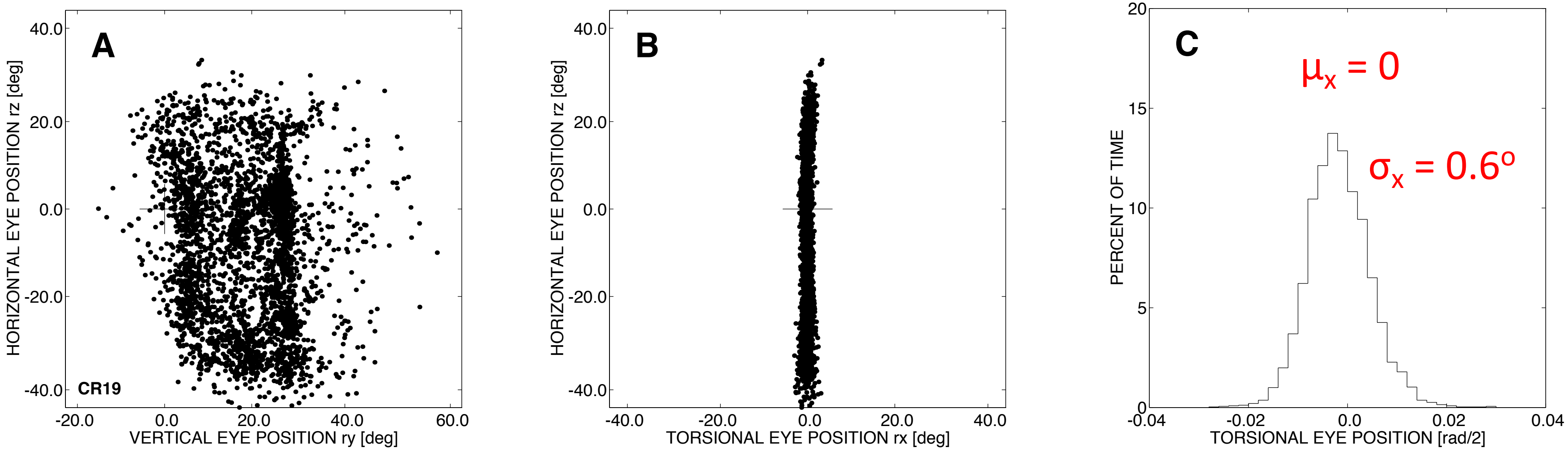


F.C. Donders observed that:

"Regardless the path taken by the eye to reach a gaze direction at (H,V), its torsional orientation is always the same" (Donders' law).

i.e., **Eye torsion = f(H, V)**
(only 2 degrees of freedom!)

Data: Measured monkey eye orientations in 3D (expressed in quaternion coordinates)



Listing's law: Ocular torsion, f(H,V) = r_x = 0

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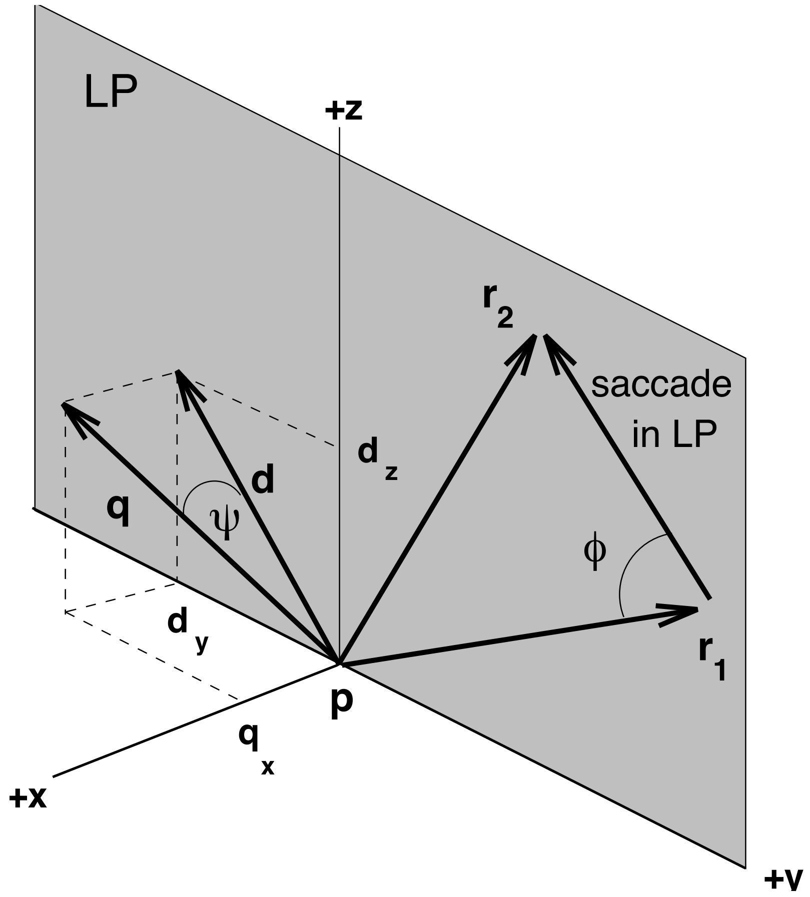
3. 3D eye-movement kinematics

The behavioural **measurements** show that:

- a saccade can be well approximated by **a single-axis rotation** from start to end
- in 3D rotation-vector coordinates, saccades are **straight lines** (geodesics) in Listing's Plane



To calculate the single rotation axis for the eye, **q**, which brings it from $\mathbf{r_1} = (0, r_{1y}, r_{1z})$ to $\mathbf{r_2} = (0, r_{2y}, r_{2z})$, we use quaternion calculus:

$$\mathbf{q = r_2 \circ r_1^{-1} = d + r_1 \times d}$$

with $\mathbf{d = r_2 - r_1}$ the straight-line saccade in LP

and note that:

- **q** is parallel to the **angular velocity** vector
- **q** has **three** degrees of freedom:

$$q_x = r_{1y}r_{2z} - r_{1z}r_{2y}$$

- but $d_x = 0$
- and also: $d_x(t) = 0 \; \forall t$

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3. 3D Eye-movement kinematics

There is good evidence that Listing's law is **not** caused by the **mechanics** of the eye (as has been suggested by others, e.g. through the action of *eye-muscle pulleys*):

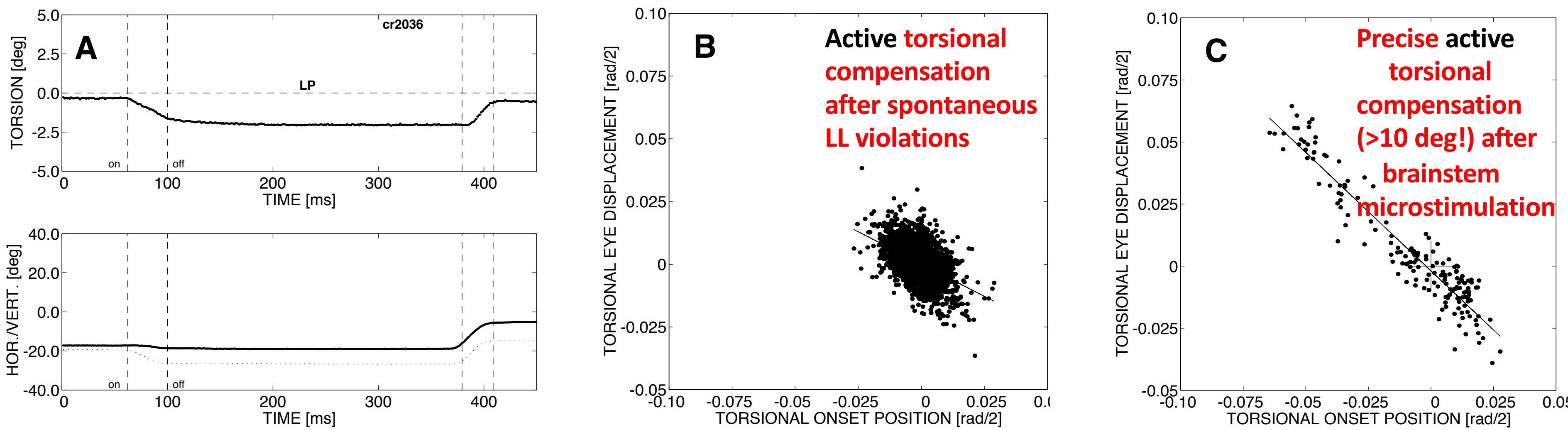
BECAUSE:

- the law is broken for near- (vergence) eye movements (*Eye torsion = f(Y)*)
- it is broken during eye-head gaze-shifts (*Eye torsion = complex function*)
- it is broken when the head is tilted re. gravity (*Eye torsion = f(tilt)*)
- it is broken for vestibular-evoked eye movements (*Eye torsion = -η·(Head torsion)*)

AND:

- there is **no torsional drift** after a small spontaneous violation of Listing's law
- the brain **keeps track** of the (small) deviations from Listing's plane between saccades:

  → voluntary saccades **DO** have 3 degrees of freedom!



→ Listing's law and Donders' law reflect **neural strategies!**

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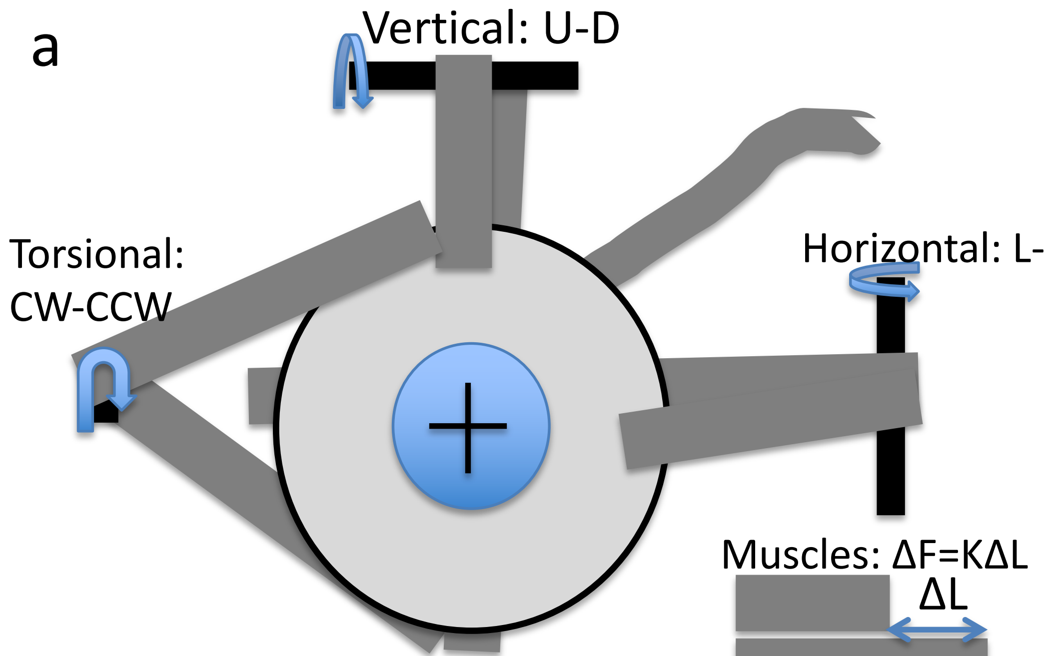
3. 3D Eye-movement kinematics

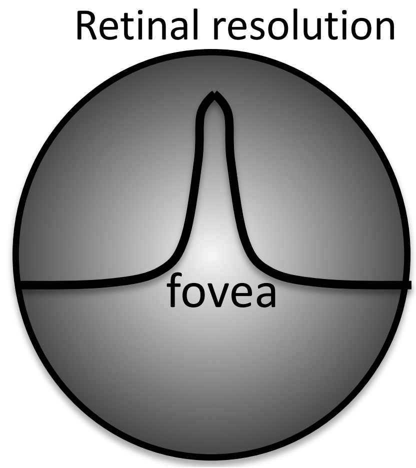
My ERC proposal: *"understanding the neural control of eye-head gaze shifts in 3D"* through a realistic biomimetic robotic eye-head control system

a



3D eye motor commands:
angular velocity axis: $[\omega_x(t), \omega_y(t), \omega_z(t)]$

b



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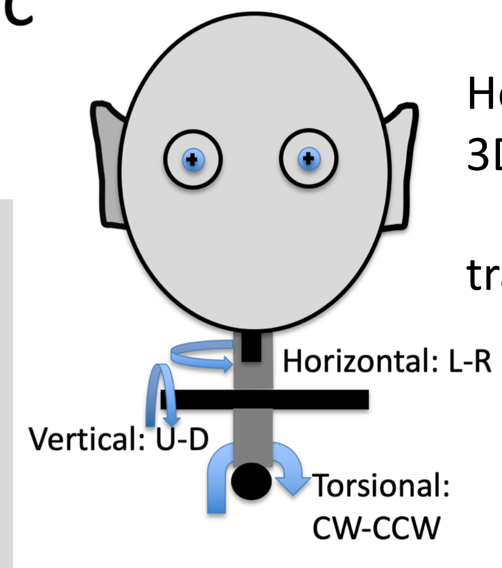

Head:
3D rotations
+
translations

Inspired by our neural (SC, brainstem, cerebellar) recordings, behavioural measurements (Listing's law, Donders' law, extended to eye-head coordination), and computational neural-network models

(Optimal control, Bayesian inference, Reinforcement learning, ...)

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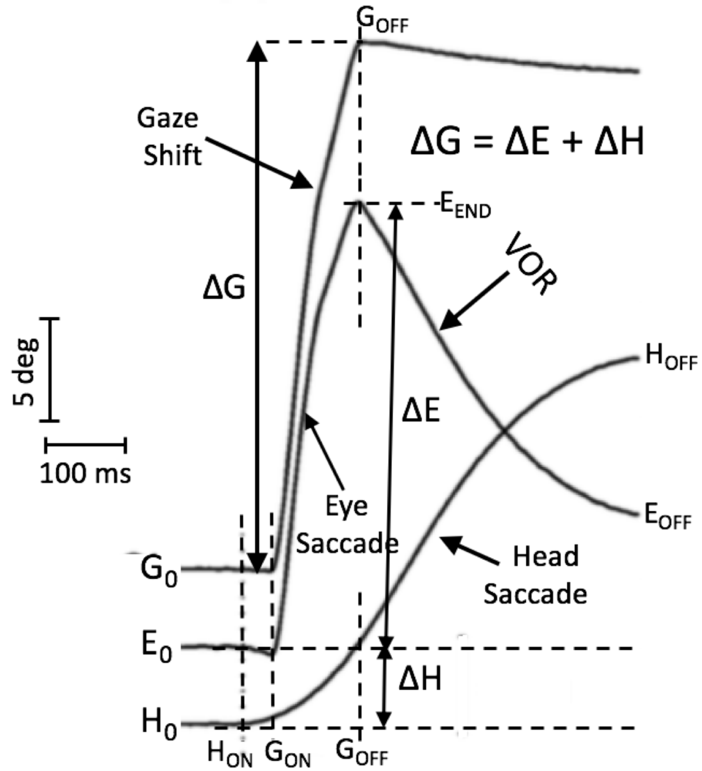
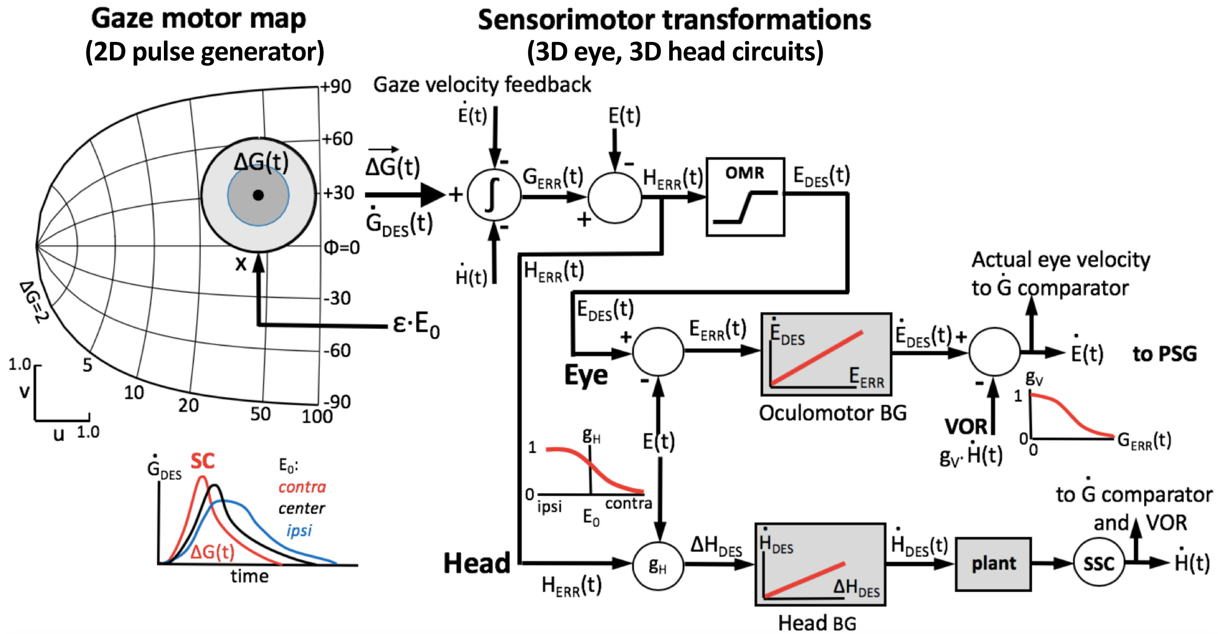
4. 3D Eye-head saccades

But: behavioural/neural SC recordings show that:
- SC population encodes the **total E-H gaze shift**
- Gaze (the eye orientation in space, $g = e \circ h$) follows Listing's law **at the end of the gaze shift**





Eye-head gaze saccades:
- Strong involvement of the 3D vestibular-ocular reflex (VOR)
- The head obeys Donders' law, but not Listing's law
- The eye-in-head trajectory no longer obeys either law!
- The eye-in-space trajectories in 3D become quite complex, as they vary with the eye-in-head and head-movement contributions to the gaze shift!

Our challenges: both computational (Nijmegen) and at the hard- and software implementations (Lisboa)

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Thank you for your attention!

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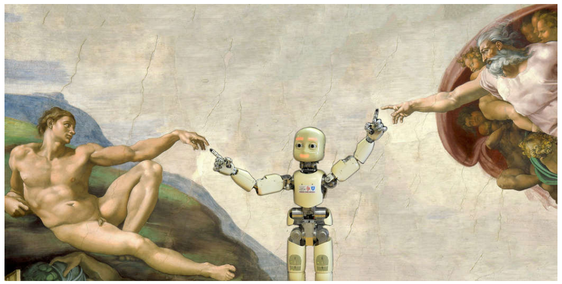

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