Learning Coordinated Eye and Head Movements: Unifying Principles and Architectures

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Bernstein Conference on
Computational Neuroscience
Berlin, 2010

Coodinated Eye/Head Movements

- ❖ Saccade: Quick change of gaze direction
- ❖ Multi-segment control of different motor systems
- ❖ Saccades are ballistic movements (Leung et al. 2008)
- ❖ Head-restrained vs. Head-free

Open Questions

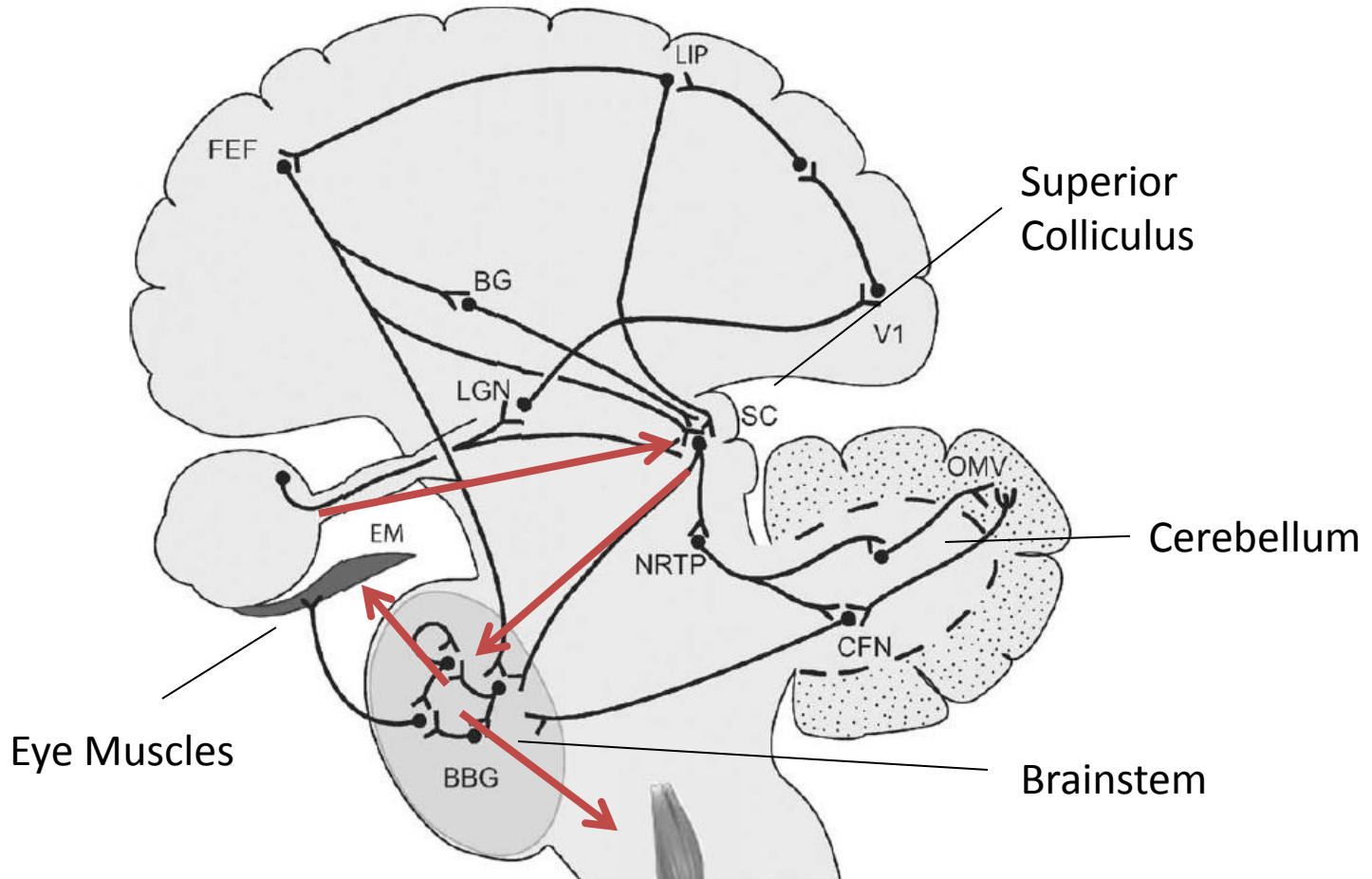➡️ Do saccade kinematics result from some optimality principle?

➡️ How does the brain learn saccade kinematics?

➡️ Is it possible to address both questions above using a single computational model?

Biological Basis of Saccadic Eye/Head Movements

Hopp & Fuchs (2004)

Eye/Head Plant Models

Eye Plant: Linear models sufficient for realistic saccades (Van Opstal et al, 1985)

$$T_1 T_2 T_3 \dddot{r}_e(t) + (T_1 T_2 + T_2 T_3 + T_3 T_1)\ddot{r}_e(t) + (T_1 + T_2 + T_3)\dot{r}_e(t) + r_e(t) = g_e u_e(t)$$

$$h_e(t) = g_e(k_1 e^{-\frac{t}{T_1}} + k_2 e^{-\frac{t}{T_2}} + k_3 e^{-\frac{t}{T_3}})$$
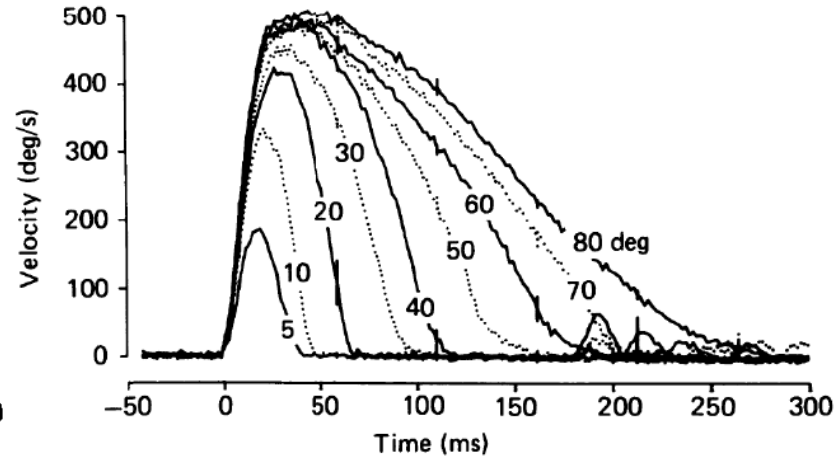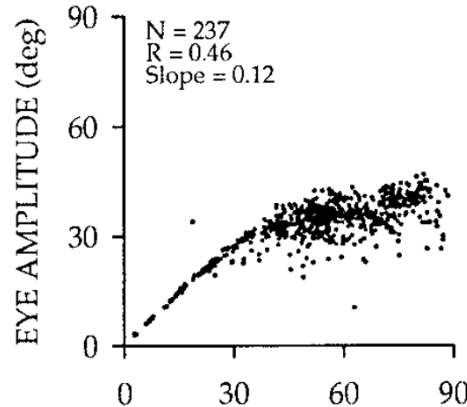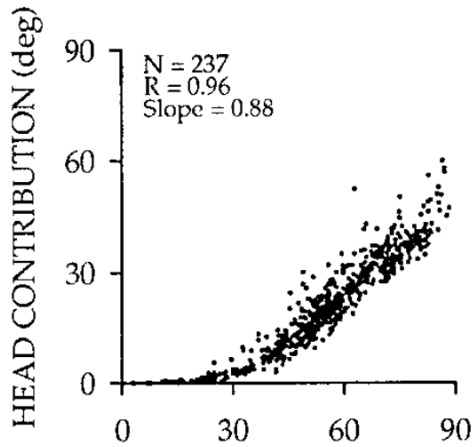
$$r_e(t) = \int_0^t u_e(\tau) h_e(t-\tau) d\tau$$

Head Plant

$$T_4 T_5 \ddot{r}_h(t) + (T_4 + T_5)\dot{r}_h(t) + r_h(t) = g_h u_h(t)$$

$$h_h(t) = g_h(k_4 e^{-\frac{t}{T_4}} + k_5 e^{-\frac{t}{T_5}})$$

$$r_h(t) = \int_0^t u_h(\tau) h_h(t-\tau) d\tau$$

The Neural Control Signal: Optimization

$u_e \, (t) = ?$ → Eye Plant

$u_h \, (t) = ?$ → Head Plant

➤ Can we derive the control signals from some optimality principle?

➤ How are the control signals optimized through learning?
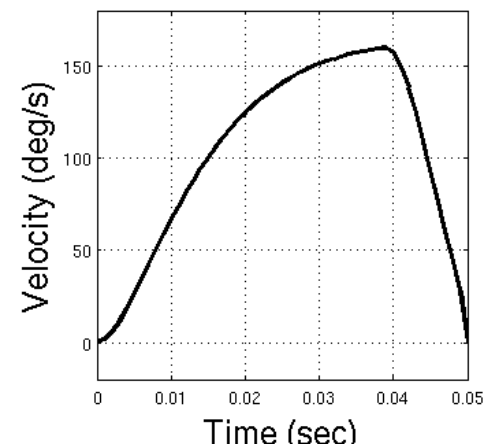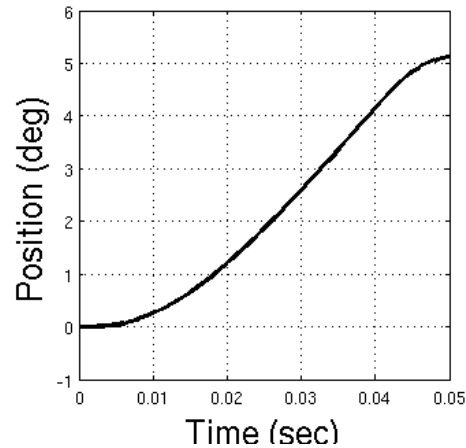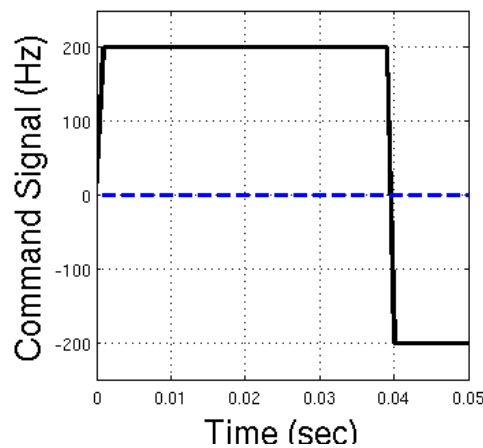
Optimality Principles

> No proper vision during saccades due to **motion blur** or **neural suppression**.

➢ **Minimum Time**

The control signal instantateously switches between its maximum positive and negative values to accelerate and decelerate the eye ("bang-bang").

Models: Optimality Principles

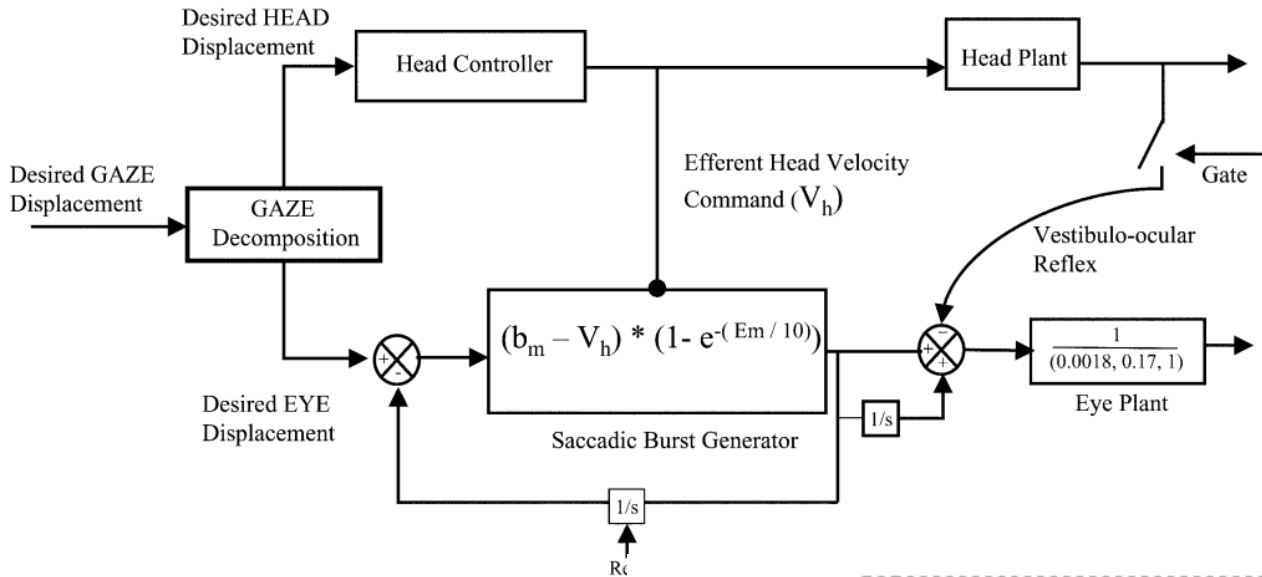➢ **Minimum Variance:** (*Harris & Wolpert, 1998; 2006*)

$$\text{Cost} = \underbrace{\int_0^T \alpha \, dt}_{\text{Movement cost}} + \underbrace{\int_T^{T+F} \beta \, e(t)^2 \, dt}_{\text{Fixation cost}} \qquad \sigma_u(t) = k|u(t)|$$

➢ **Minimum Effort** (*Kardamakis & Moschovakis, 2009*)

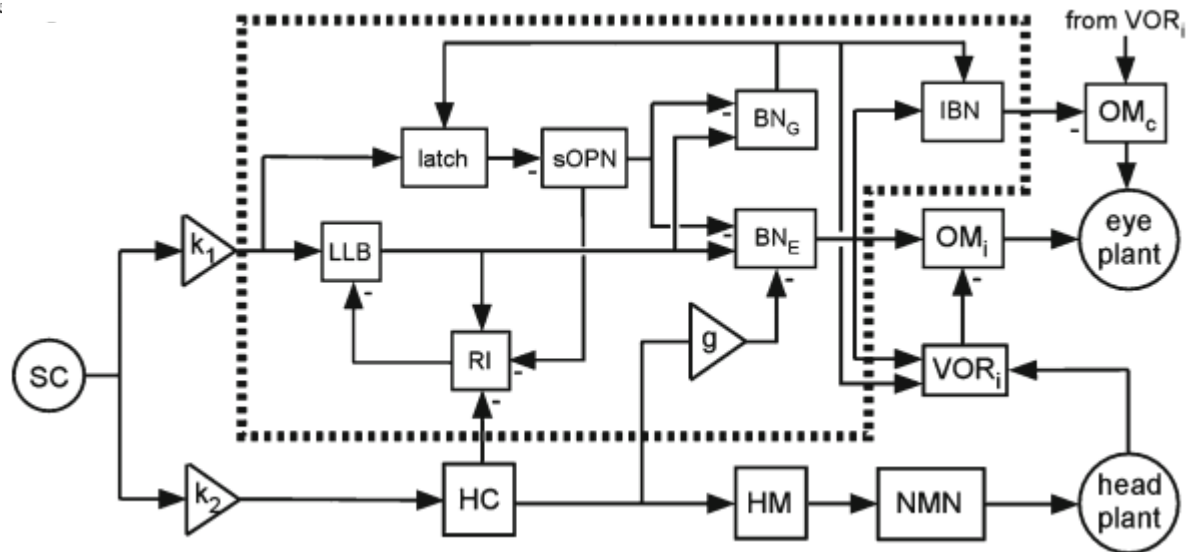$$\text{Cost} = \int_0^T [\alpha(x_e) u_e^2 + \beta u_h^2] dt$$

$$\alpha(x_e) = \alpha_0 + \alpha_1 x_e + \alpha_2 x_e^2$$
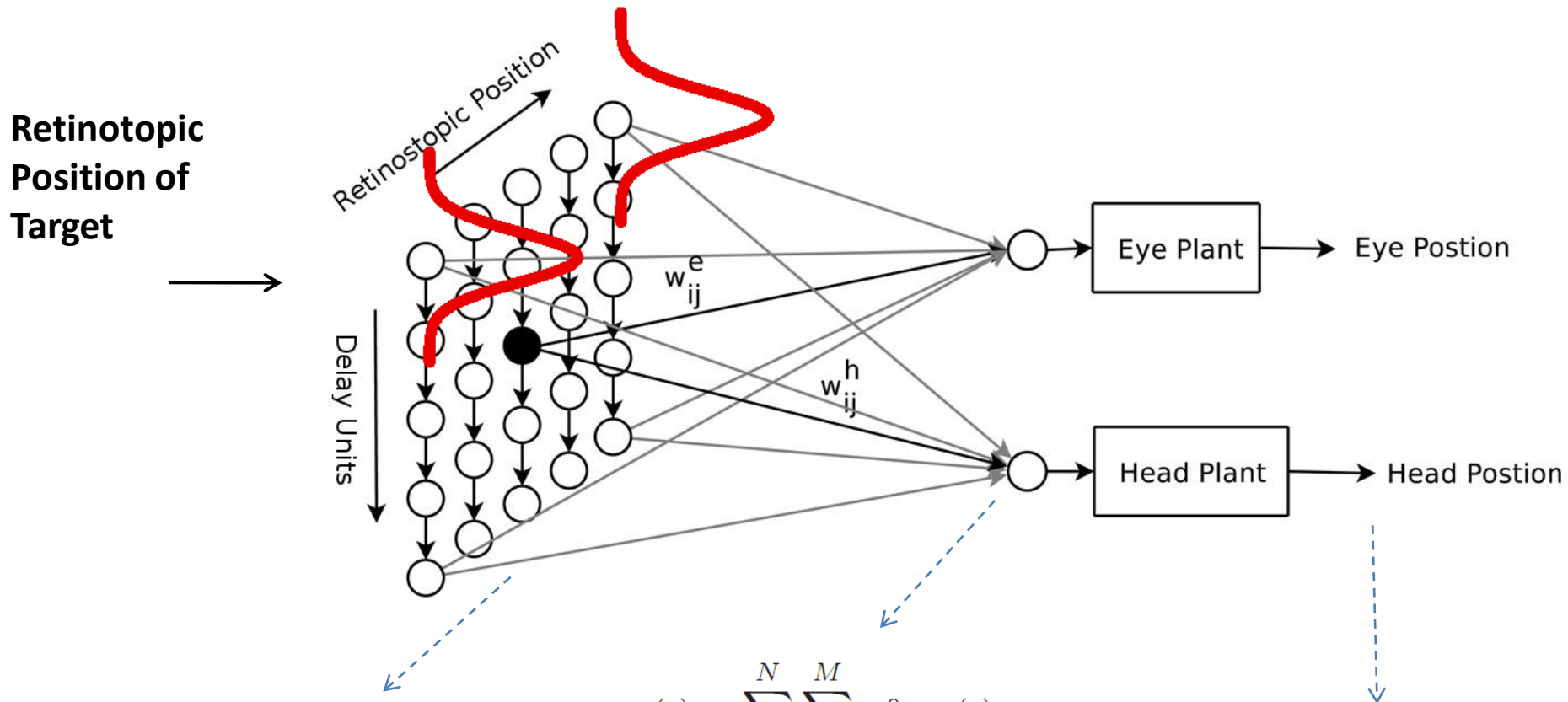
Models: Neural Architectures

Freedman (2001)

Kardamakis et al. (2010)

The Open-loop Neural Controller

Retinotopic Position of Target

Retinostopic Position

Delay Units

w_{ij}^{e}

w_{ij}^{h}

Eye Plant → Eye Postion

Head Plant → Head Postion

$$s_{ij}(t) = A \exp\left(-\frac{(i - \frac{t}{\Delta t})^2}{2\sigma^2}\right)$$

$$u_{\mathrm{e}}(t) = \sum_{j=1}^{N}\sum_{i=1}^{M} w_{ij}^{\mathrm{e}} s_{ij}(t)$$

$$u_{\mathrm{h}}(t) = \sum_{j=1}^{N}\sum_{i=1}^{M} w_{ij}^{\mathrm{h}} s_{ij}(t)$$

$$r_{\mathrm{e}}(t) = \int_{0}^{t} u_{\mathrm{e}}(\tau) h_{\mathrm{e}}(t - \tau)d\tau,$$

$$r_{\mathrm{h}}(t) = \int_{0}^{t} u_{\mathrm{h}}(\tau) h_{\mathrm{h}}(t - \tau)d\tau$$

The Cost Function
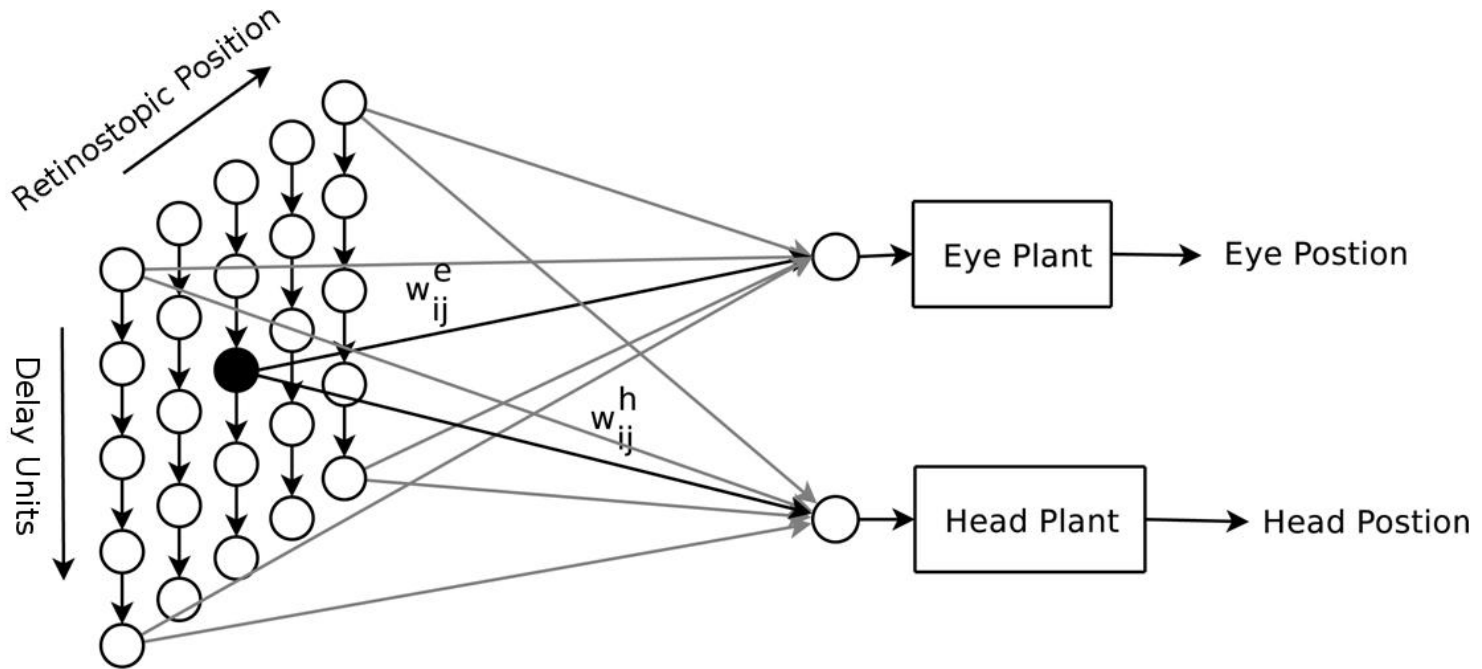
1. **The gaze should reach the target as soon as possible and then stand still on the target position.**

2. **The power of the neural command signal should be constrained.**

$$E = \left| \int_0^T |r_{\text{vis}}(t)| dt \right| + \left| \sum_{j=1}^{N} \sum_{i=1}^{M} (\alpha_{\text{e}}|w_{ij}^{\text{e}}|^n + \alpha_{\text{h}}|w_{ij}^{\text{h}}|^n) \right|$$

Adaptation: Gradient Descent on the Cost Function

$$\Delta w_{ij}^{\mathrm{e}} = \delta_{ij}^{\mathrm{e}} \int_0^T \mathrm{sign}(r_{\mathrm{vis}}(t)) \left(\int_0^t s_{ij}(\tau) h_{\mathrm{e}}(t-\tau) d\tau \right) dt - n\delta_{ij}^{\mathrm{e}} \alpha_{\mathrm{e}} (w_{ij}^{\mathrm{e}})^{(n-1)}$$

$$\Delta w_{ij}^{\mathrm{h}} = \delta_{ij}^{\mathrm{h}} \int_0^T \mathrm{sign}(r_{\mathrm{vis}}(t)) \left(\int_0^t s_{ij}(\tau) h_{\mathrm{h}}(t-\tau) d\tau \right) dt - n\delta_{ij}^{\mathrm{h}} \alpha_{\mathrm{h}} (w_{ij}^{\mathrm{h}})^{(n-1)}$$

Adaptive Parameters: w^{e} , w^{h}

Free Parameters: n, α_{e} , α_{h} , σ
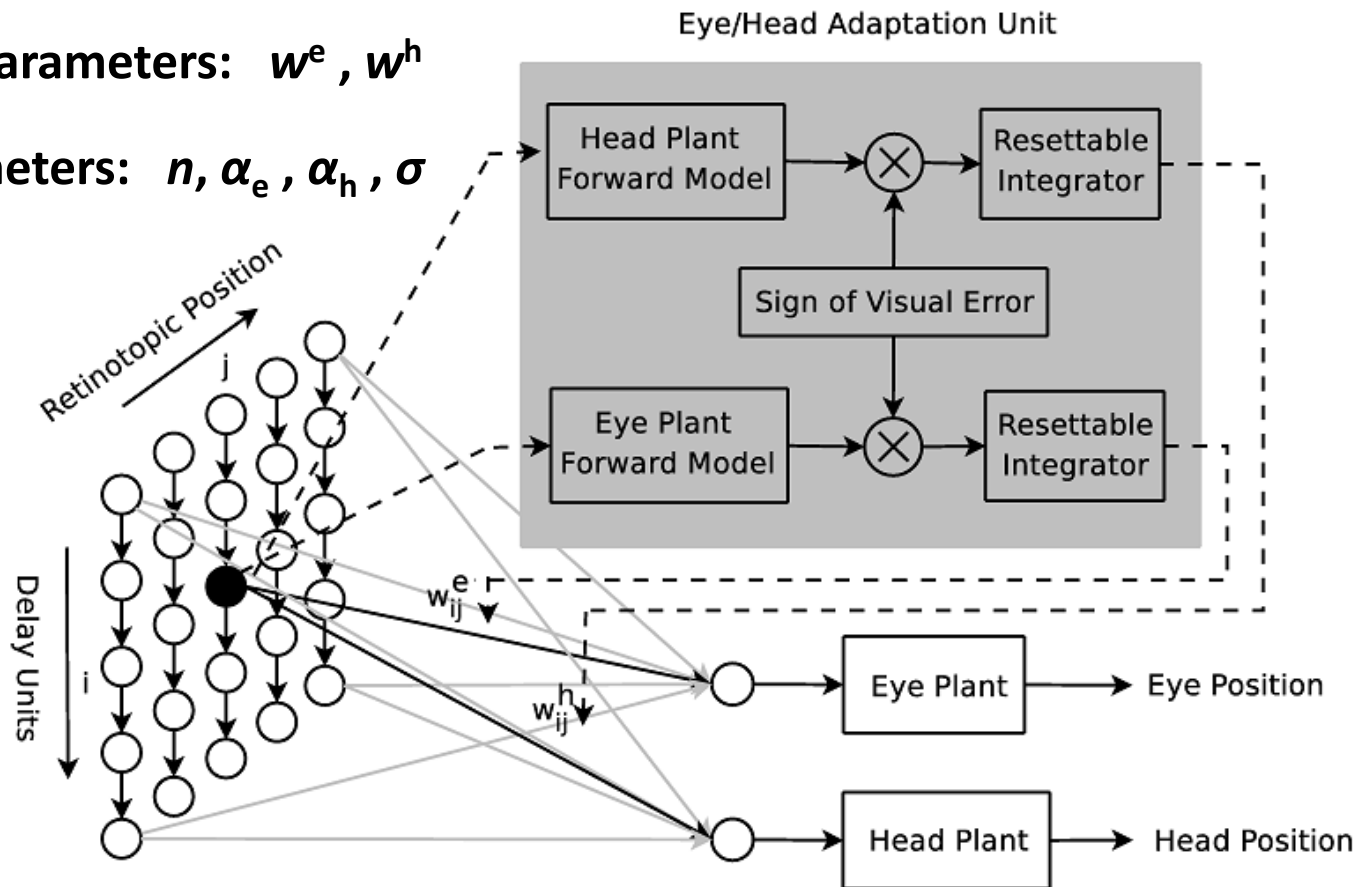
Results: Head-Restrained Saccades
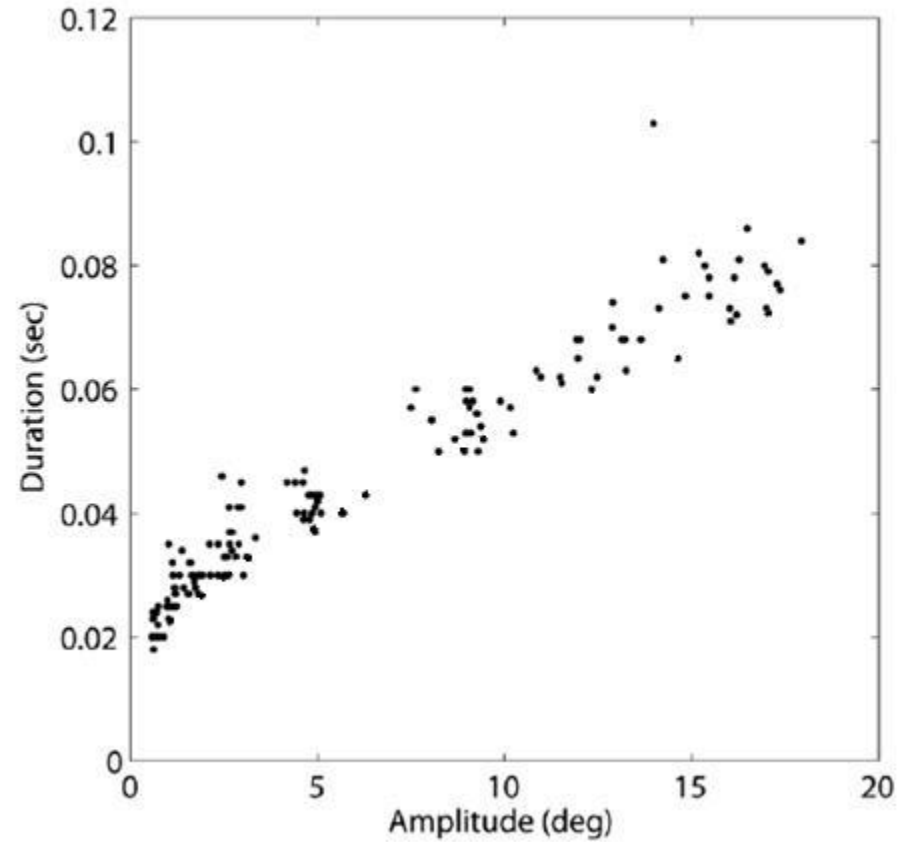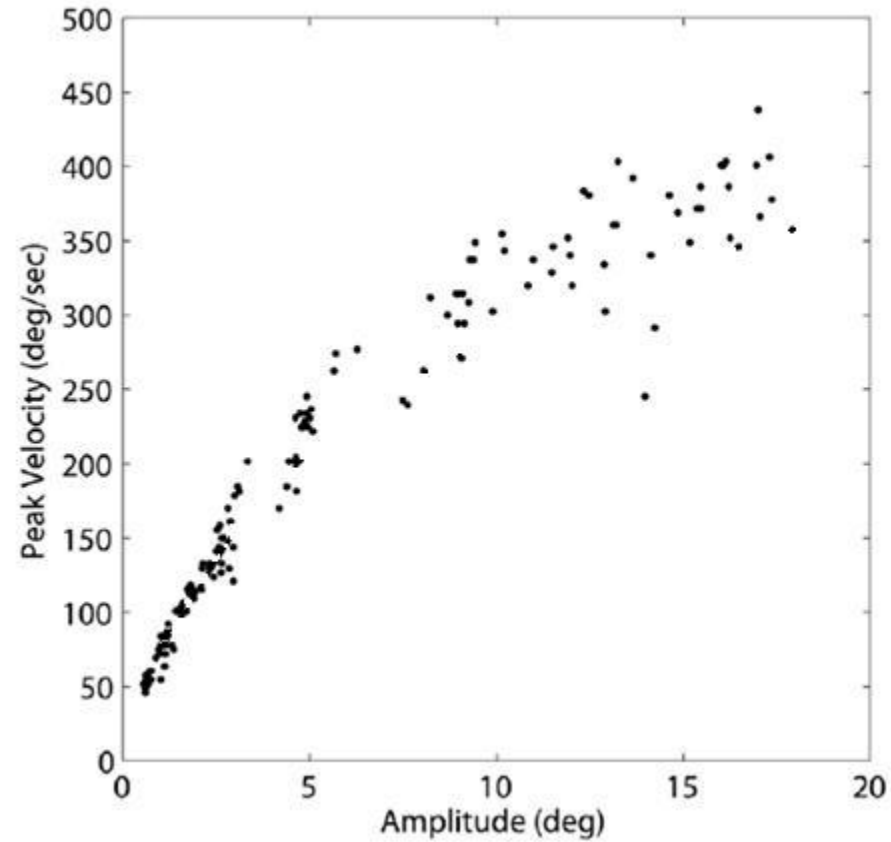
.... Experimental Data (Harwood et al., 1999)

Results: Head-Restrained Saccades
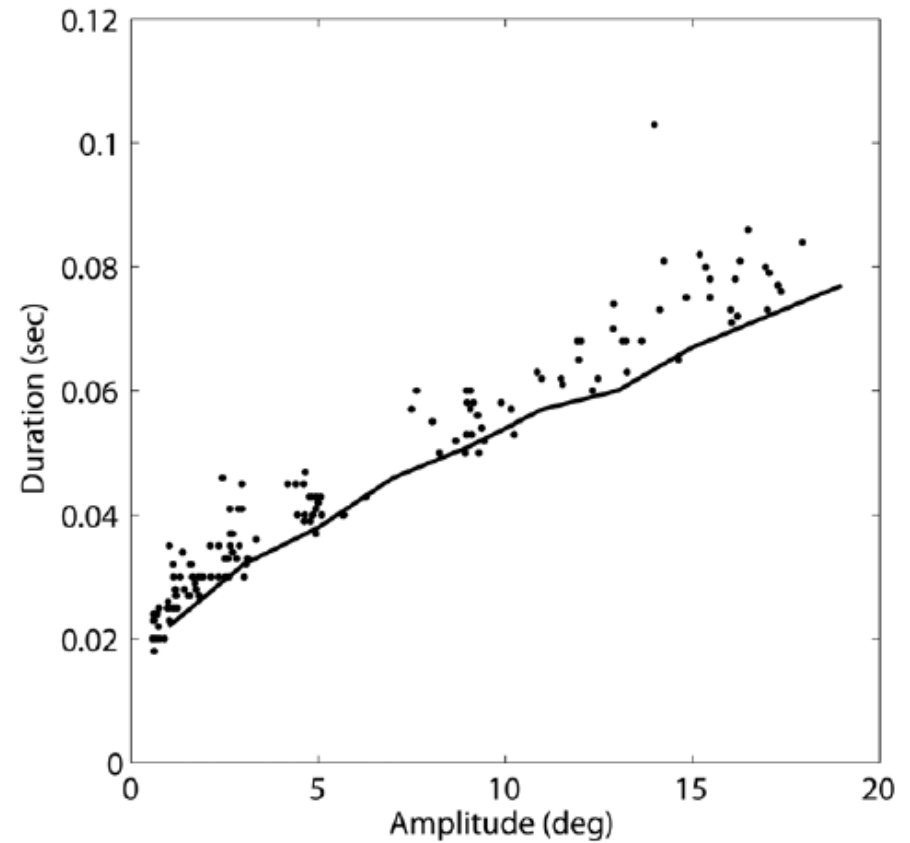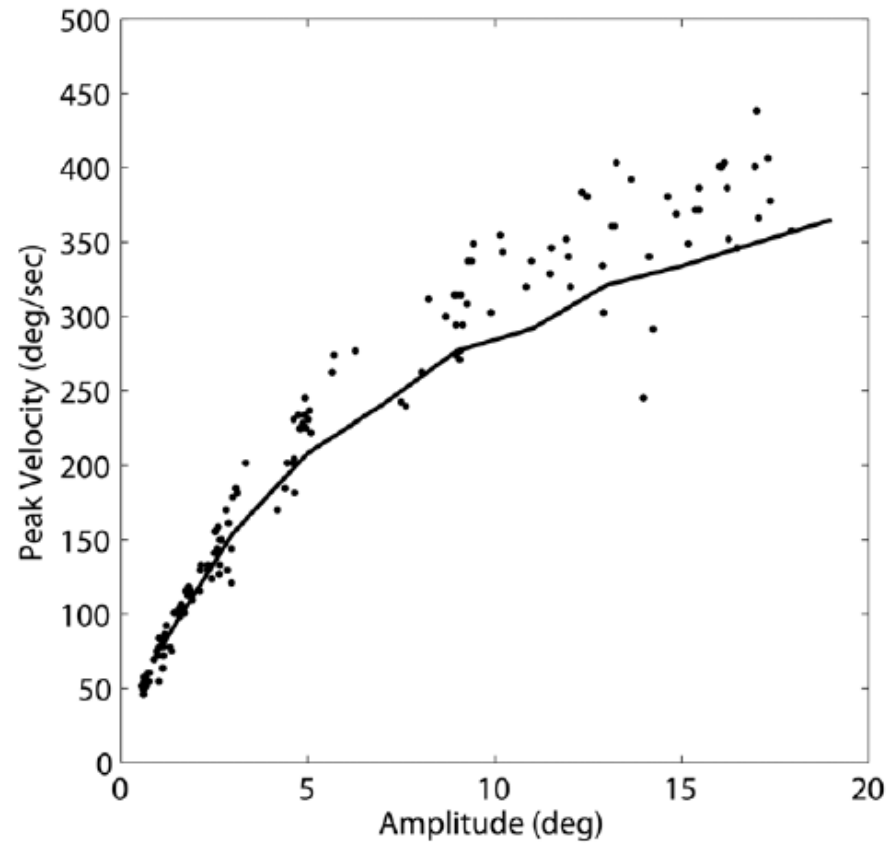
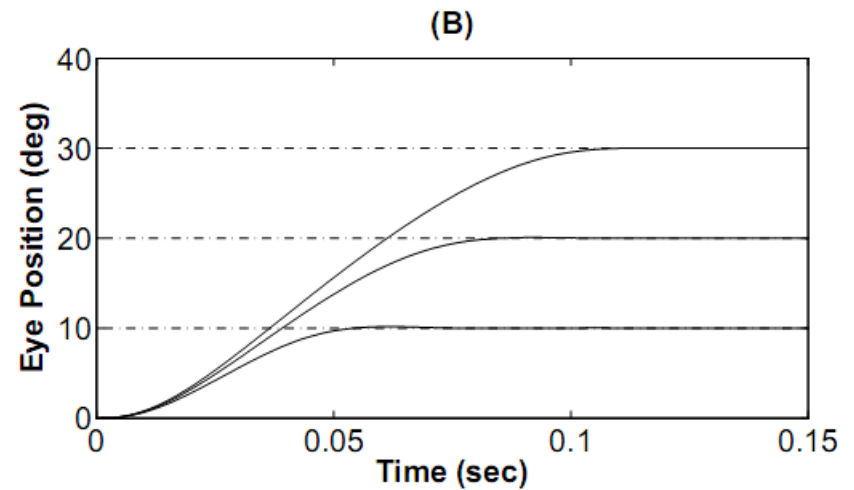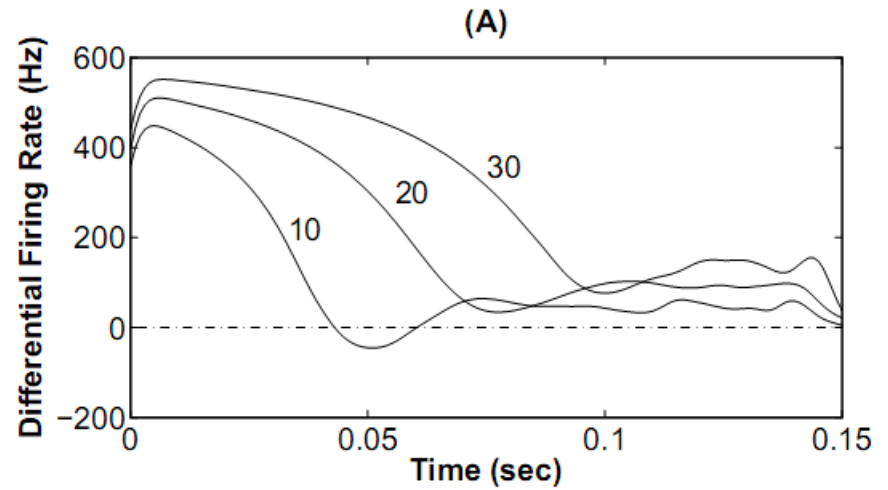........ Experimental Data (Harwood et al., 1999)

⸻ Model Result (**σ = 0.002, α$_e$ = 0.016, n=4**)
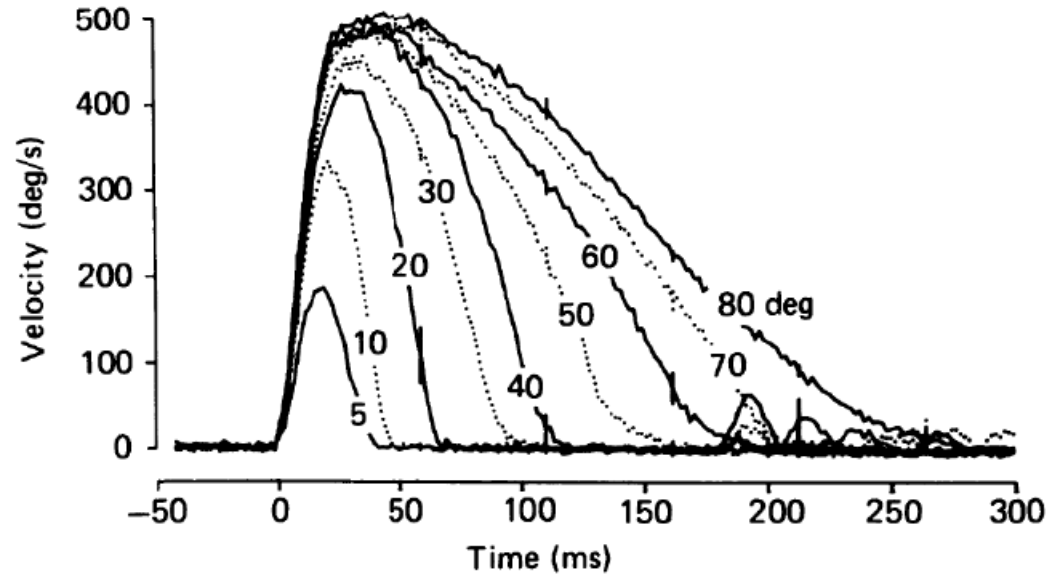
Results: Head-Restrained Saccades
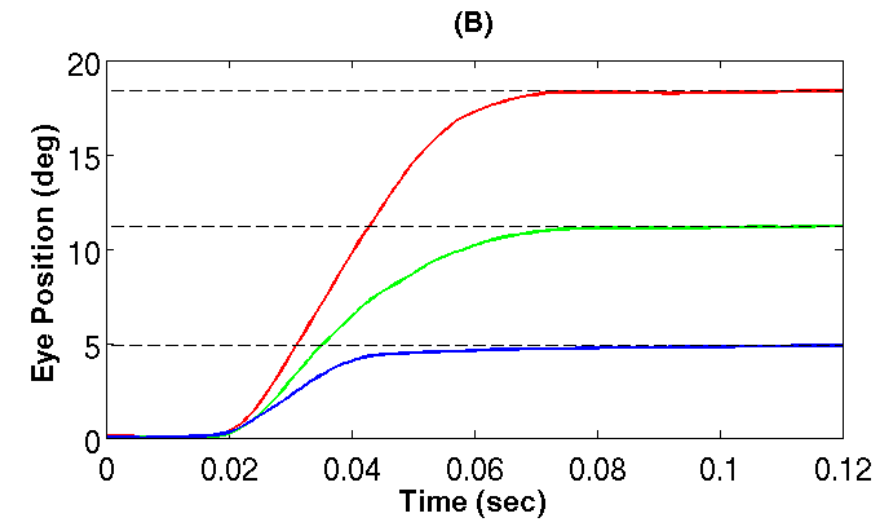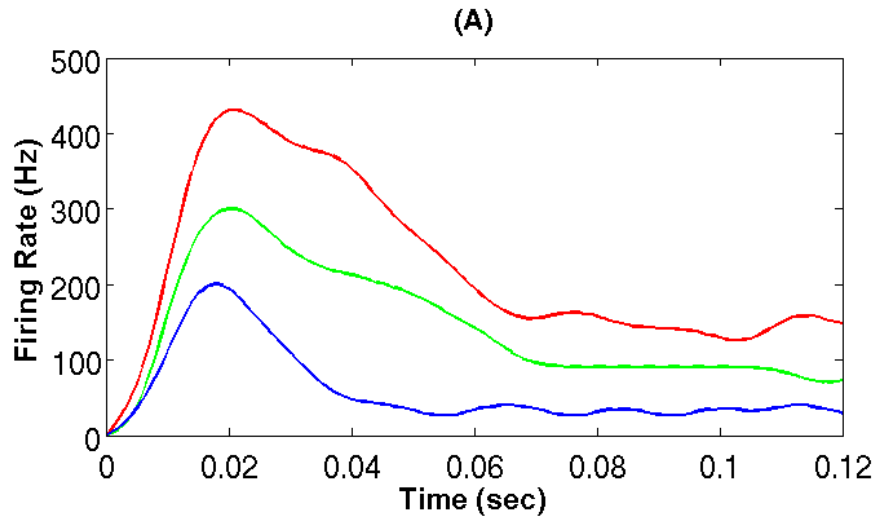
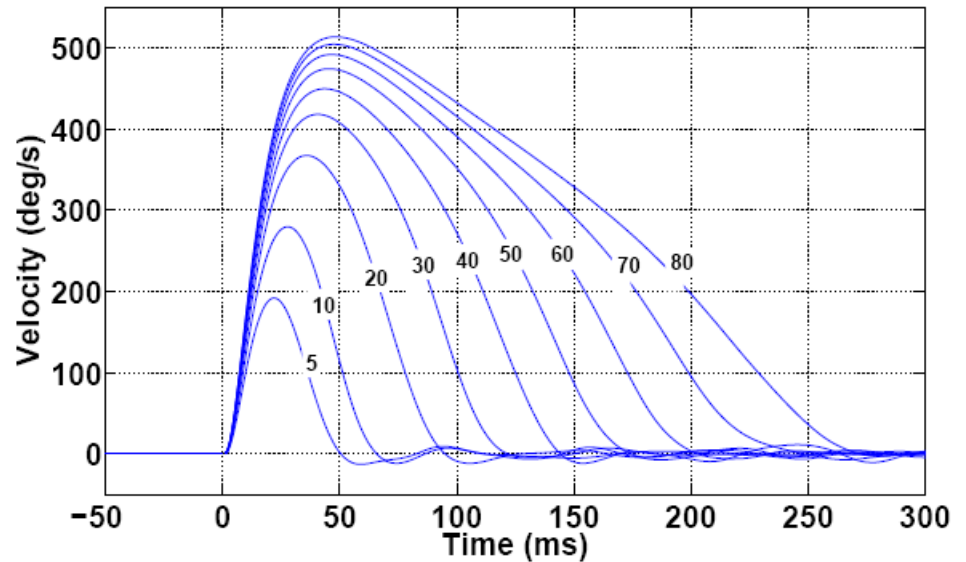**Experimental Results
(Sylvestre & Cullen, 1999)**

Model Simulation Results
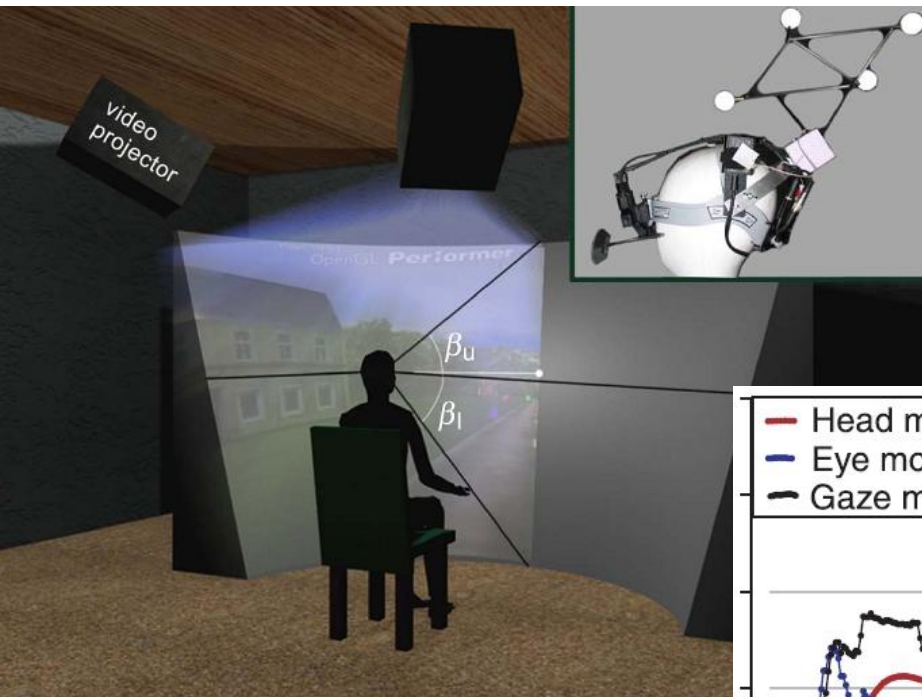
Results: Head-Restrained Saccades
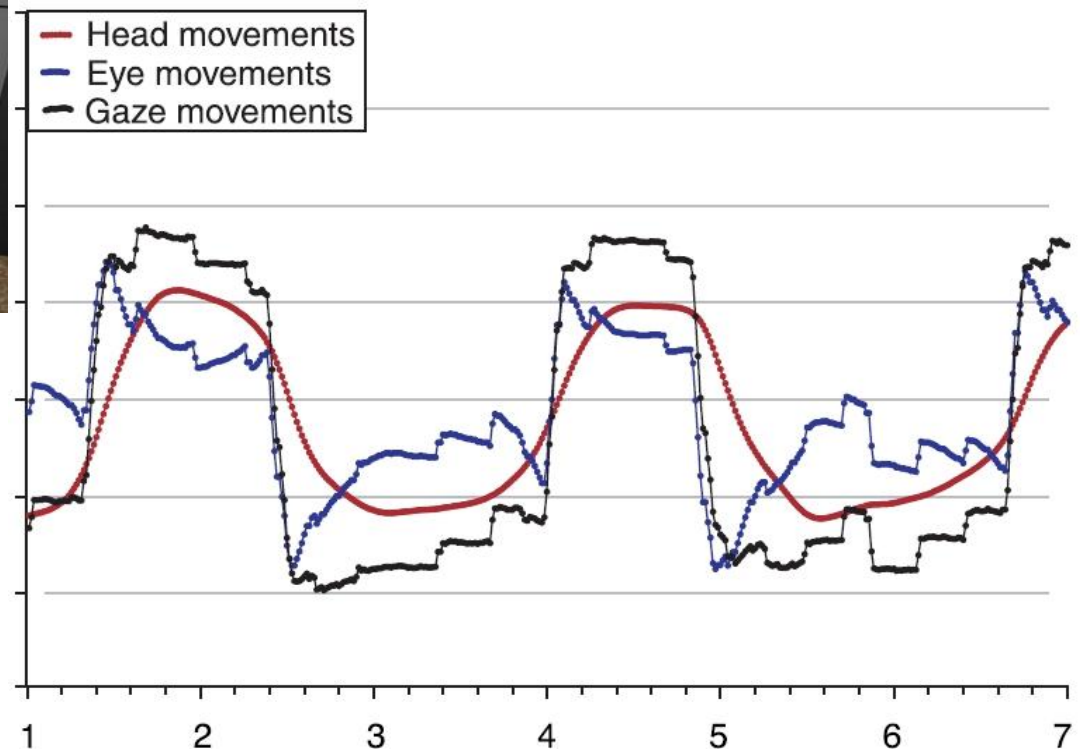

**Experimental Results
(Collewijn et al., 1988)**
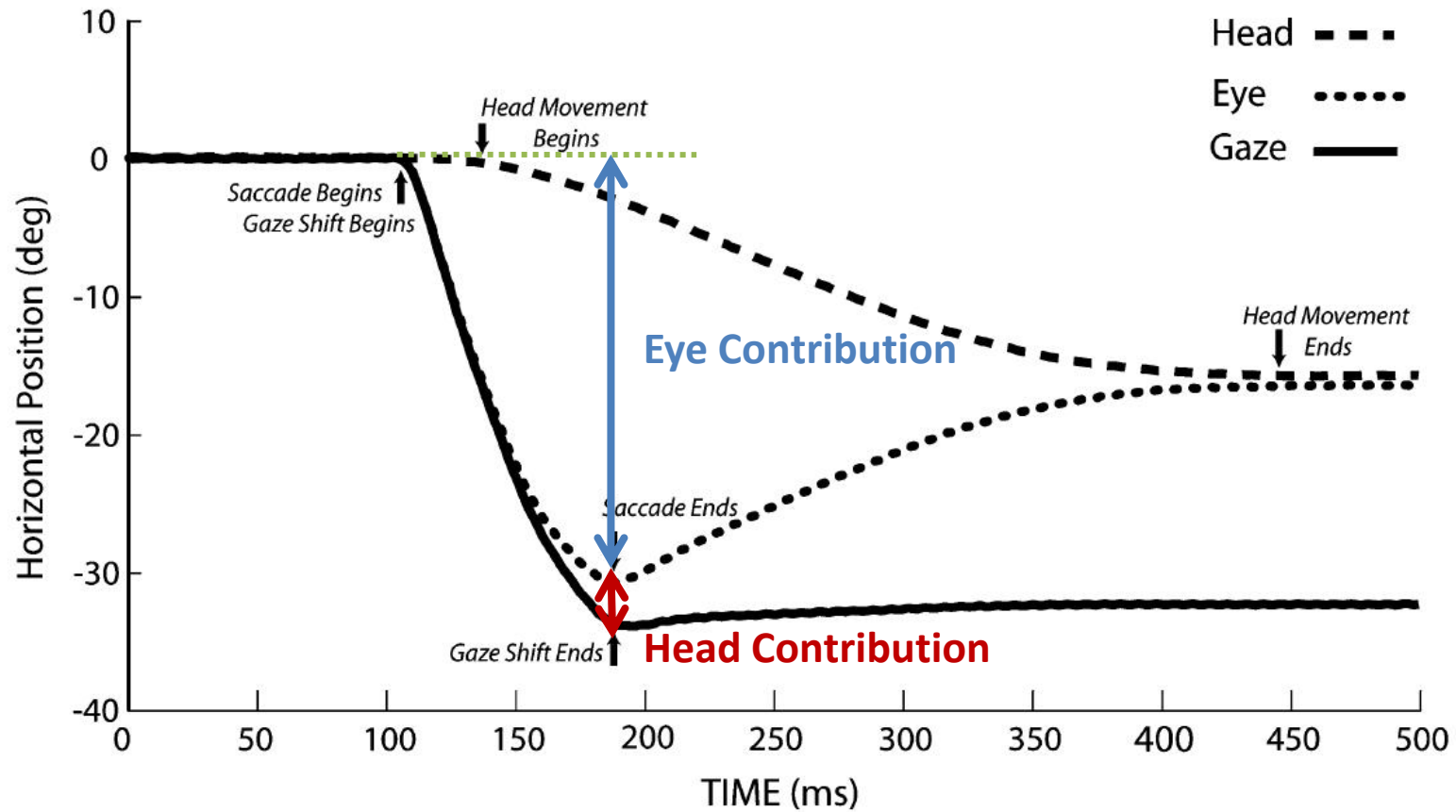
Model Simulation Results
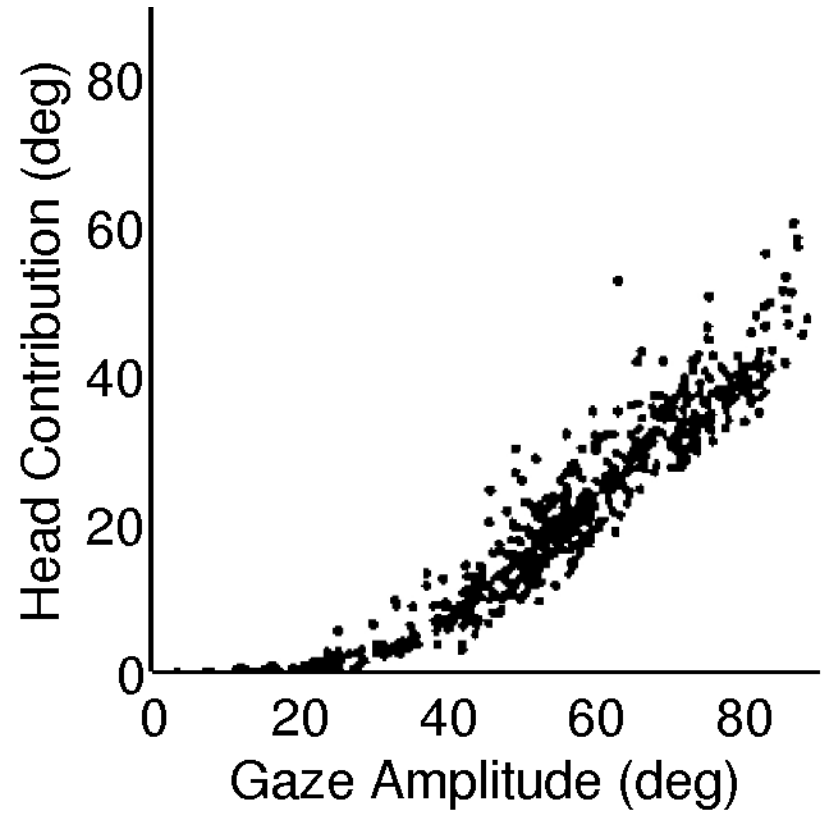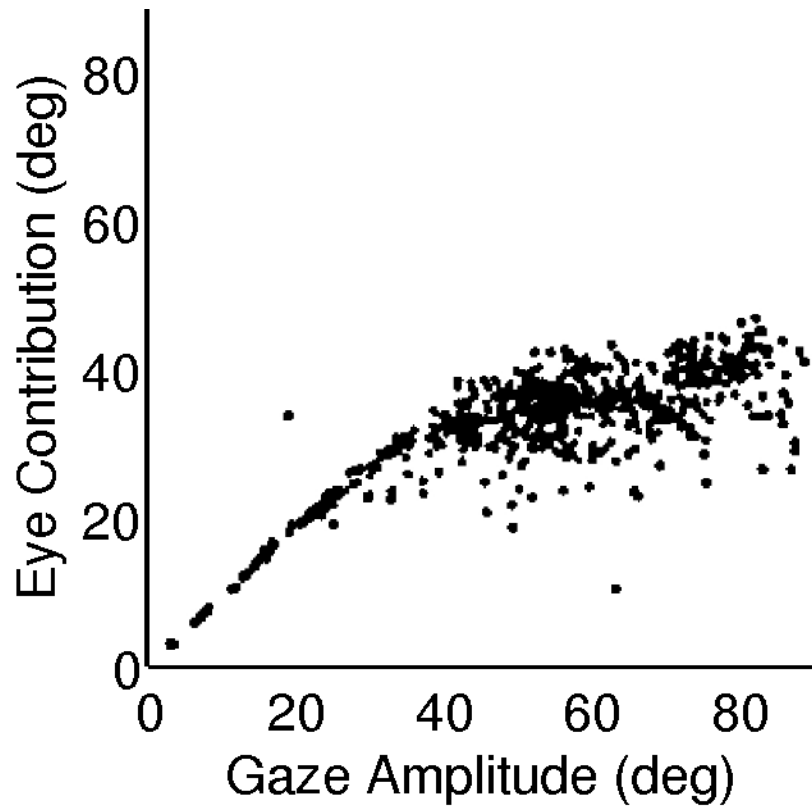
Results: Head-Free Saccades

Head-free gaze shift of human subjects during a visual search paradigm (Hardiess et al, 2008)
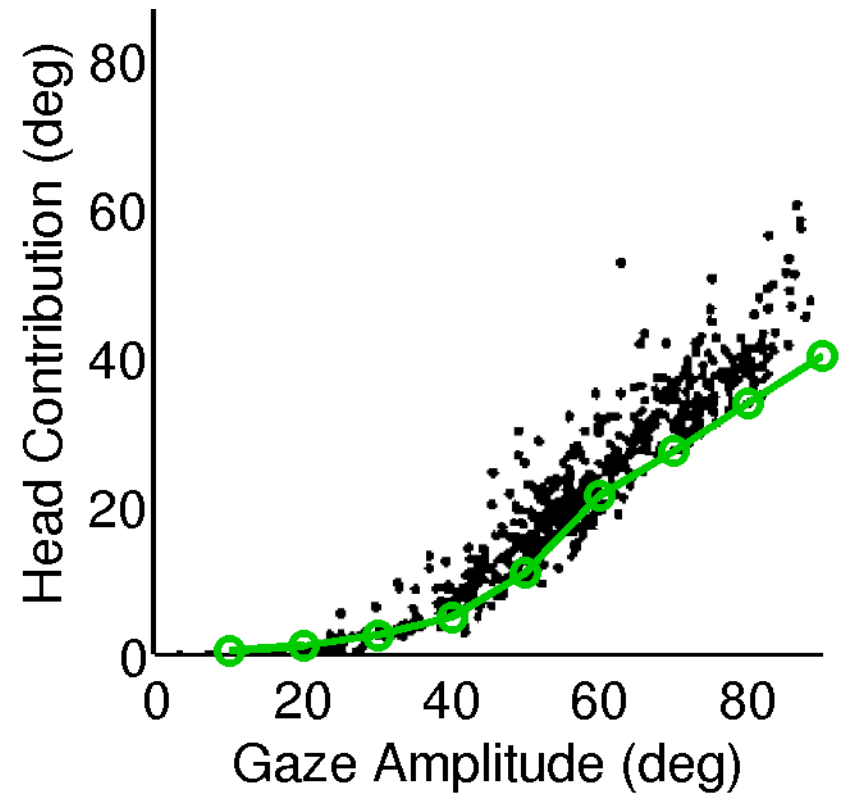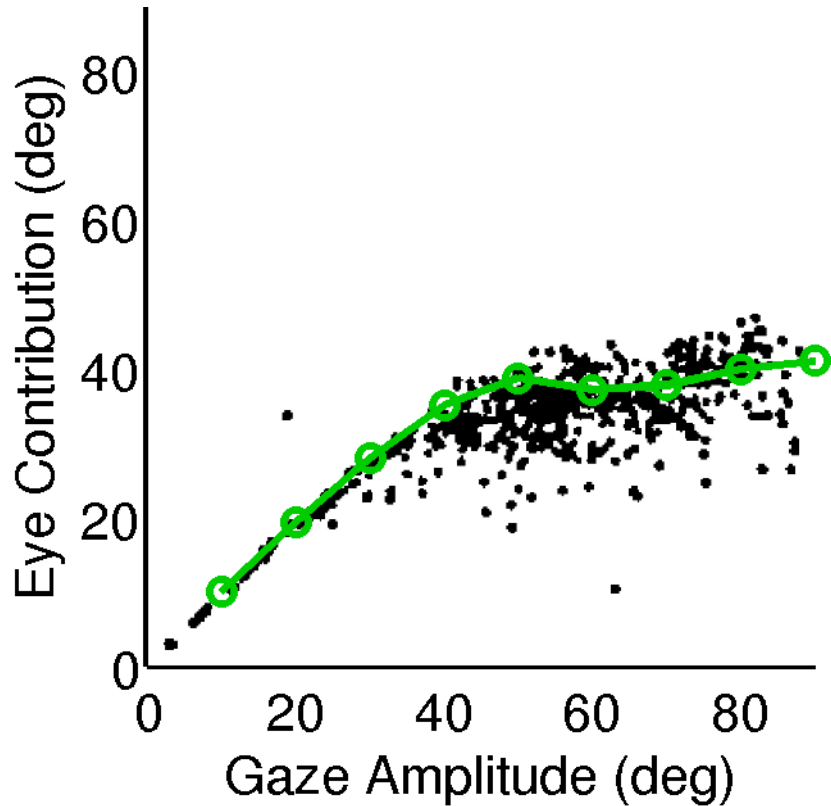
Results: Head-Free Saccades

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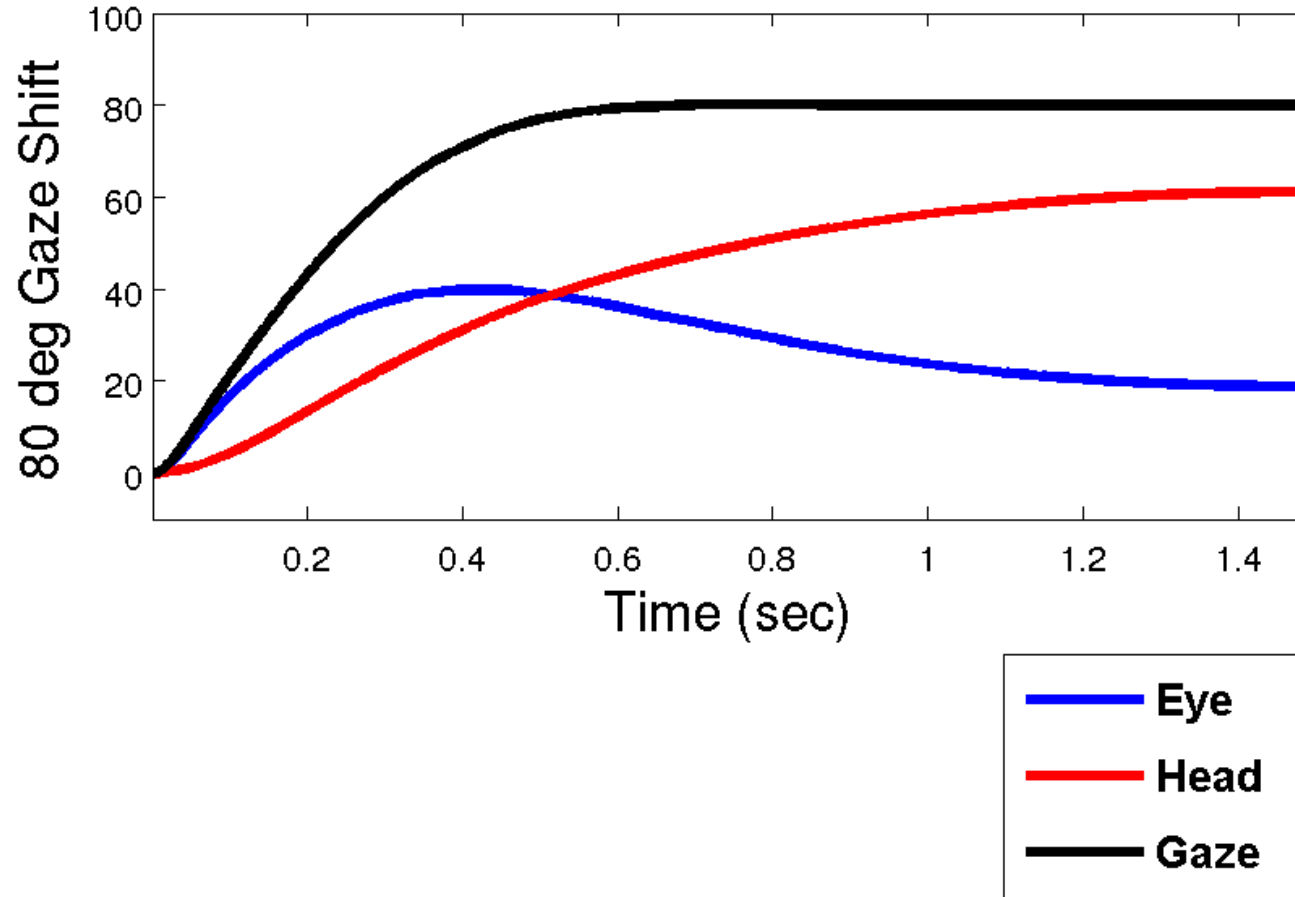

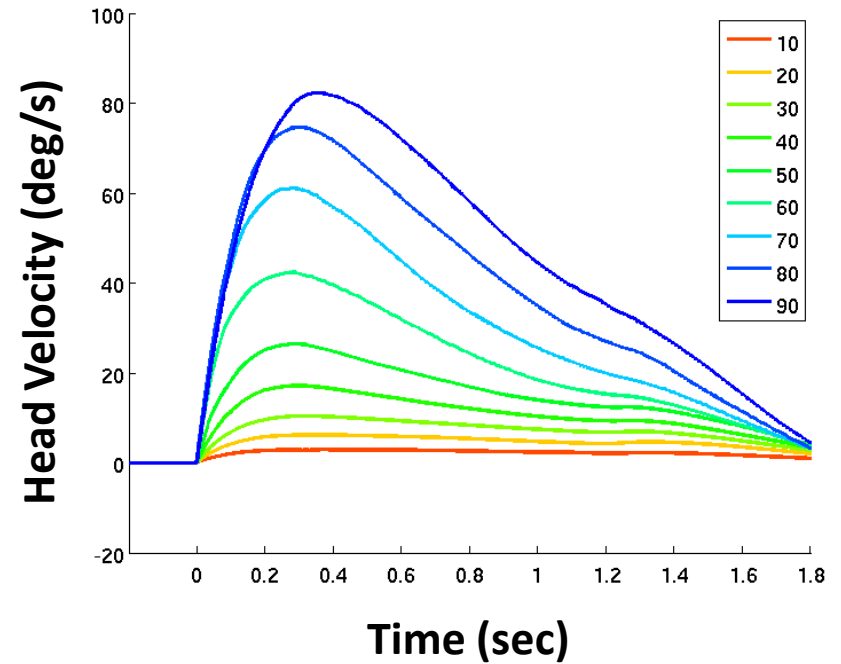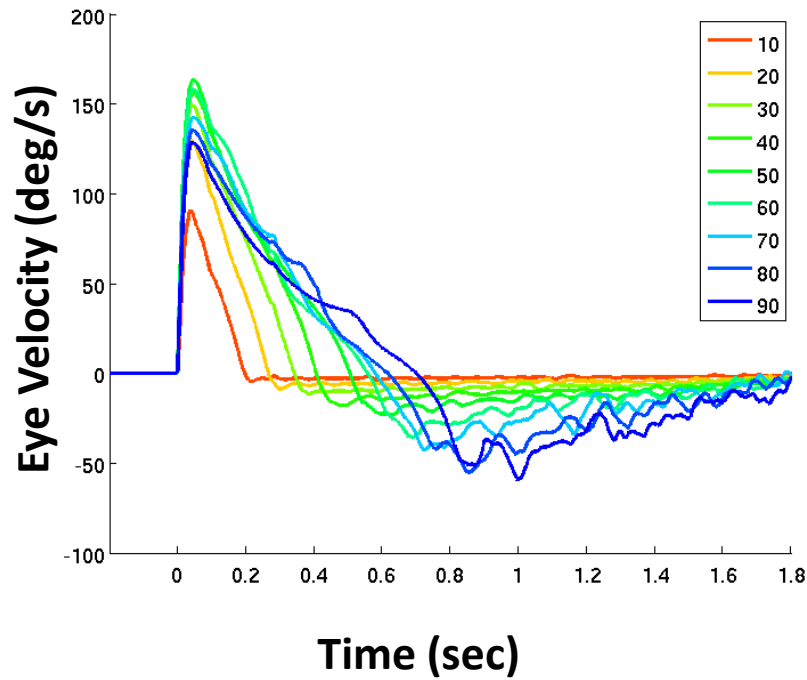...... Experimental Data (Freedman and Sparks; 1997)

Results: Head-Free Saccades

Experimental Data (Freedman and Sparks; 1997)

Model Result (σ = 0.002, α_e = 1.0, α_h = 0.016, n=4)
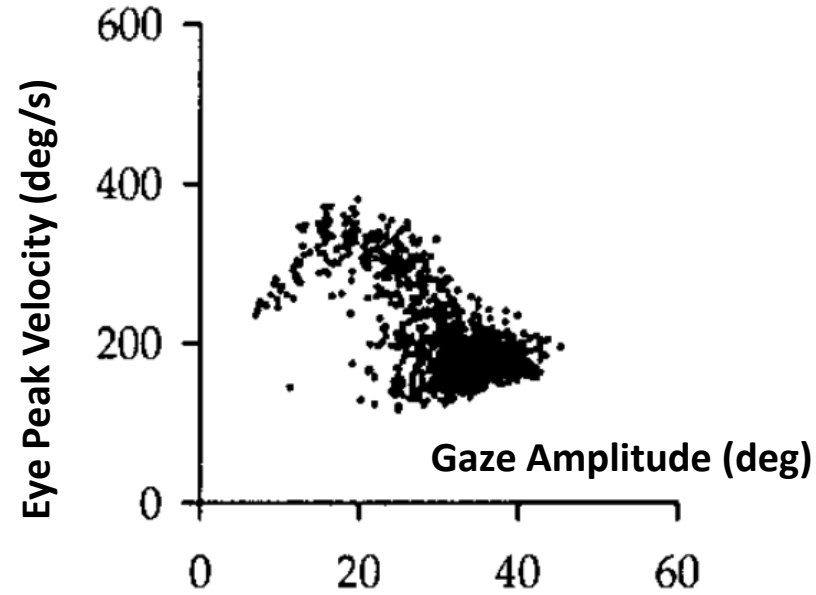
Results: Head-Free Saccades
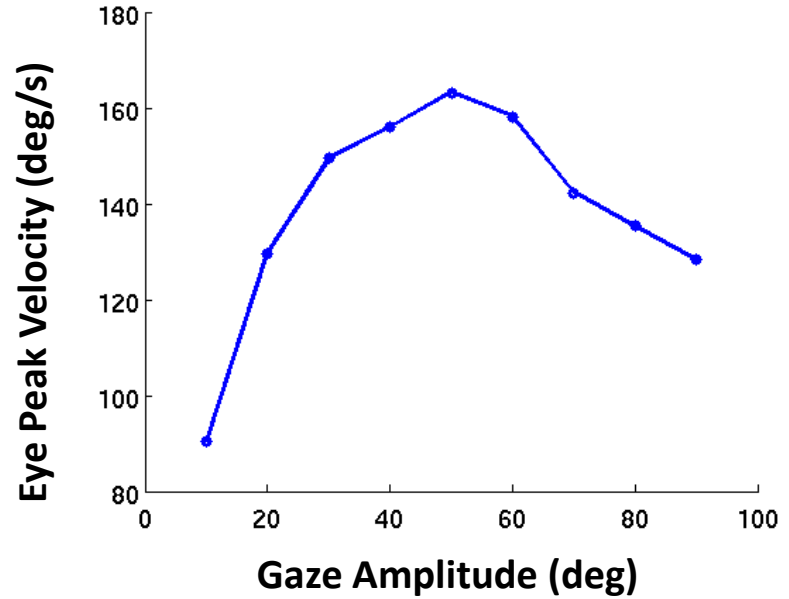
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Model Result (σ = 0.002, α_e = 1.0, α_h = 0.016, n=4)

Results: Head-Free Saccades

Experimental Data
(Freedman and Sparks; 1997)

Model Result

Conclusion

➡ Simple open-loop neural controller capable of reproducing biologically realistic eye and head movements.

➡ The model is based on an adaptation mechanism that on one hand is local and biologically plausible and on the other hand minimizes a cost function, therefore it creates a bridge between **optimality principles** and **neural architectures**.

Future Directions:

❖ Different initial eye positions

❖ Forward model learning

❖ Other ballistic movements