New model of gaze tracking in 2D: Novel architecture with independent gaze and head controllers

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Outline

- General introduction
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Reorienting gaze to a new center of interest recruits both eye and head movement.
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Coordination movements (gaze and head with a common goal)
Introduction

- Reorienting gaze to a new center of interest recruits both eye and head movement.
- Coordinated movements (gaze and head with a common goal)
  - A simple movement: A-B jump
Introduction

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  - A simple movement: A-B jump
  - Gaze saccade ≡ “automatic” command
Reorienting gaze to a new center of interest recruits both eye and head movement.

Coordinated movements (gaze and head with a common goal)
- **A simple movement**: A-B jump
- Gaze saccade ≡ “automatic” command

Dissociated movements (gaze and head with separate goals)
Introduction

- Reorienting gaze to a new center of interest recruits both eye and head movement.
- Coordinated movements (gaze and head with a common goal)
  - A simple movement: A-B jump
  - Gaze saccade ≡ “automatic” command
- Dissociated movements (gaze and head with separate goals)
  - A more complex movement: AB-C jump
Reorienting gaze to a new center of interest recruits both eye and head movement.

**Coordinated movements (gaze and head with a common goal)**
- A simple movement: A-B jump
- Gaze saccade ≡ “automatic” command

**Dissociated movements (gaze and head with separate goals)**
- A more complex movement: AB-C jump
- Head ≡ “cognitive” command
Current models

Two major theoretical hypotheses:
Current models

Two major theoretical hypotheses:

Feedforward gaze control
Current models

Two major theoretical hypotheses:

Feedback gaze control
Our model

Desired behavior and structure
Our model

Desired behavior and structure

- Our model will reject perturbations on gaze
Our model
Desired behavior and structure

- Our model will reject perturbations on gaze
- Our model will account for both coordinated and dissociated movements
Our model

Desired behavior and structure

- Our model will reject perturbations on gaze
- Our model will account for both coordinated and dissociated movements
- We will structure the model like the anatomy
Our model
Brain structures modelled

Superior colliculus
Our model
Brain structures modelled
Cerebellum
Our model

Global structure

\[ \dot{H}^* \]

\[ \Delta G \]

\[ \Delta H \]

CBLM (Feedback)

SC (Drive)

Head independent

\[ \dot{H}^* \]

\[ \dot{E}^* \]

Premotor brainstem

Spinal cord

VOR

EYE Plant

HEAD Plant

SCC

CAP

Premotor brainstem

Pierre Daye (UCLouvain)
Our model
Superior Colliculus drive

CBLM (Feedback) → SC (Drive) → Head independent → \( \dot{H}^* \)

\( \dot{H}^* \) → Premotor brainstem → VOR → EYE Plant

\( \dot{H}^* \) → Spinal cord → HEAD Plant

\( \Delta G \) → SC (Drive)

\( \Delta H \) → Head independent → \( \dot{H}^* \)

SCC → \( \dot{H}^* \)

CAP → \( \dot{H}^* \)
Our model
Superior Colliculus drive

Inputs
1. Desired gaze displacement
2. Inhibition from the Cerebellum

Output
1. Gaze directional drive

Initial burst of activity sent to eye and head motoneurons

ΔG

SC (Drive)

Premotor brainstem

Spinal cord

VOR

EYE Plant

HEAD Plant

Pierre Daye (UCLouvain)
Our model
Superior Colliculus drive

- Inputs

ΔG

SC (Drive)

Premotor brainstem

VOR

EYE Plant

Spinal cord

HEAD Plant

Pierre Daye (UCLouvain) 2D gaze model Sept 23th, 2009 9 / 33
Our model
Superior Colliculus drive

- Inputs
  - Desired gaze displacement
Our model
Superior Colliculus drive

- **Inputs**
  1. Desired gaze displacement
  2. Inhibition from the Cerebellum
Our model
Superior Colliculus drive

- Inputs
  1. Desired gaze displacement
  2. Inhibition from the Cerebellum

- Output
Our model
Superior Colliculus drive

- Inputs
  1. Desired gaze displacement
  2. Inhibition from the Cerebellum

- Output
  1. Gaze directional drive
Our model
Superior Colliculus drive

- Inputs
  1. Desired gaze displacement
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- Output
  1. Gaze directional drive

- Initial burst of activity sent to eye and head motoneurons
Our model

Cerebellum “feedback” drive
Our model

Cerebellum “feedback” drive

We have a diagram that illustrates the interactions between different components in the cerebellum feedback system. The inputs to the system include:

1. Desired gaze displacement
2. Eye velocity efference copy
3. Head velocity from the SCC

The outputs of the system are:

1. “Feedback” corrective drive to the eye
2. Error signal to the vestibular nuclei
3. Inhibition signal to the Superior Colliculus

The diagram shows how these components are interconnected, with arrows indicating the flow of information. The goal is to achieve quick corrective drive to the eye movement.

ΔG

H*

CBLM (Feedback)

E*

Premotor brainstem

VOR

EYE Plant

SC (Drive)
Our model
Cerebellum “feedback” drive

- Inputs

- Outputs
Our model
Cerebellum “feedback” drive

• Inputs
  - Desired gaze displacement

- Desired gaze displacement

- Eye velocity efference copy

- Head velocity from the SCC

- “Feedback” corrective drive to the eye

- Error signal to the vestibular nuclei

- Inhibition signal to the Superior Colliculus

- Quick corrective drive to the eye

\[ \Delta G \]
\[ \dot{H}^* \]
\[ \dot{E}^* \]

CBLM (Feedback)

Premotor brainstem

VOR

EYE Plant

SC (Drive)
Our model
Cerebellum “feedback” drive

• Inputs
  1. Desired gaze displacement
  2. Eye velocity efference copy
Our model
Cerebellum “feedback” drive

- Inputs
  - Desired gaze displacement
  - Eye velocity efference copy
  - Head velocity from the SCC

![Diagram showing the model's inputs and outputs with notation: Desired gaze displacement (ΔG), Eye velocity efference copy (E*), Head velocity from the SCC (H*), CBLM (Feedback), Premotor brainstem, VOR, and EYE Plant.]
Our model
Cerebellum “feedback” drive

- **Inputs**
  1. Desired gaze displacement
  2. Eye velocity efference copy
  3. Head velocity from the SCC

- **Outputs**
Our model
Cerebellum “feedback” drive

• Inputs
  1. Desired gaze displacement
  2. Eye velocity efference copy
  3. Head velocity from the SCC

• Outputs
  1. “Feedback” corrective drive to the eye

\[ \Delta G \]

\[ \dot{H}^{*} \]

\[ \dot{E}^{*} \]

\[ \text{CBLM (Feedback)} \]

\[ \text{Premotor brainstem} \]

\[ \text{VOR} \]

\[ \text{EYE Plant} \]

\[ \text{SC (Drive)} \]
Our model
Cerebellum “feedback” drive

- **Inputs**
  1. Desired gaze displacement
  2. Eye velocity efference copy
  3. Head velocity from the SCC

- **Outputs**
  1. “Feedback” corrective drive to the eye
  2. Error signal to the vestibular nuclei

---

**Diagram:**
- **Inputs:**
  - Desired gaze displacement
  - Eye velocity efference copy
  - Head velocity from the SCC
- **Outputs:**
  - “Feedback” corrective drive to the eye
  - Error signal to the vestibular nuclei

**Nodes:**
- **CBLM (Feedback)**
- **Premotor brainstem**
- **VOR**
- **EYE Plant**
- **SC (Drive)**
Our model
Cerebellum “feedback” drive

- **Inputs**
  1. Desired gaze displacement
  2. Eye velocity efference copy
  3. Head velocity from the SCC

- **Outputs**
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Quick corrective drive to the eye movement
Our model

Independent head controller
Our model

Independent head controller

\[ \Delta H \]

Head independent

\[ \dot{H}^* \]

\[ \ddot{H}^* \]

Spinal cord

HEAD Plant

Desired head displacement

Head velocity from the SCC

Command signal to the head motoneurons

Desired head position

\[ \Delta H \]

Premotor brainstem

Spinal cord

VOR

Plant

SCC

CAP
Our model
Independent head controller

Inputs

- Desired head displacement
- Head velocity from the SCC

Output

- Command signal to the head motoneurons
- Desired head position $\Delta H$

CBLM (Feedback)
SC (Drive)
Head

$\dot{H}^*$

$\dot{H}^*$ estimator

Spinal cord

HEAD Plant

Premotor brainstem
Spinal cord
Our model
Independent head controller

- Inputs
  1. Desired head displacement
Our model

Independent head controller

- Inputs
  1. Desired head displacement
  2. Head velocity from the SCC
Our model
Independent head controller

- **Inputs**
  1. Desired head displacement
  2. Head velocity from the SCC

- **Output**
Our model
Independent head controller

- **Inputs**
  1. Desired head displacement
  2. Head velocity from the SCC

- **Output**
  1. Command signal to the head motoneurons
Our model
Independent head controller

- **Inputs**
  1. Desired head displacement
  2. Head velocity from the SCC

- **Output**
  1. Command signal to the head motoneurons

Desired head position
Model behavior: Typical example

Position

- $\text{Targets}$
- $\text{Head}_S$
- $\text{Gazes}_S$
- $\text{Eye}_H$

Graphs showing the relationship between $V$ [deg] and $H$ [deg] over time [sec].
Model behavior: Typical example

Pathways discharge

- CBLM (Feedback)
- SC (Drive)
- Head independent
- Head estimator
- Premotor brainstem
- Spinal cord
- VOR
- EYE Plant
- HEAD Plant

Symbols:
- $\Delta G$
- $\Delta H$
- $\dot{H}^*$
- $\dot{E}^*$
- $\dot{H}^*$

Feedback loop:
- CBLM to SC

Drive loop:
- SC to Head independent
- Head independent to Head estimator

Estimator:
- Head estimator to Head independent

VOR:
- VOR to EYE Plant

2D gaze model

Pierre Daye (UCLouvain)
Model behavior

Two steps: Step 1: Superior Colliculus and Cerebellum → Gaze control

- Superior Colliculus discharges → head and eye movements reduce gaze error
Model behavior
Two steps: Step 1: Superior Colliculus and Cerebellum → Gaze control

- Superior Colliculus discharges → head and eye movements reduce gaze error
- Cerebellum discharges to quickly correct (via an eye displacement) any perturbation on the gaze movement
Model behavior

Two steps: Step 1: Superior Colliculus and Cerebellum → Gaze control

- Superior Colliculus discharges → head and eye movements reduce gaze error
- Cerebellum discharges to quickly correct (via an eye displacement) any perturbation on the gaze movement
- Gaze on the target
  → VOR ON ($\dot{E} = -\dot{H}$)
  → ($\dot{G} = 0$)
Model behavior

Two steps: Step 2: Cerebellum → Head final position control

- Superior Colliculus does not discharge
Model behavior

Two steps: Step 2: Cerebellum → Head final position control

- Superior Colliculus does not discharge
- Cerebellum gaze controller does not discharge
Model behavior

Two steps: Step 2: Cerebellum $\rightarrow$ Head final position control

- Superior Colliculus does not discharge
- Cerebellum gaze controller does not discharge
- Cerebellum head controller controls head position
Model behavior

Two steps: Step 2: Cerebellum $\rightarrow$ Head final position control

- Superior Colliculus does not discharge
- Cerebellum gaze controller does not discharge
- Cerebellum head controller controls head position
- Gaze on the target
  $\rightarrow$ VOR ON ($\dot{E} = -\dot{H}$)
  $\rightarrow$ ($\ddot{G} = 0$)
Model behavior: Typical example
Pathways discharge

\[ \begin{array}{c|c|c|c}
\text{Time [sec]} & 0 & 0.25 & 0.5 & 0.75 & 1 \\
\hline
\text{SC H} & 1 & 0.5 & 0 & 0 & -0.5 & -1 \\
\text{CB H} & 0.5 & 1 & 0.5 & 0 & 0 & -0.5 \\
\text{CBg H} & 0 & 0.5 & 1 & 0.5 & 0 & 0 \\
\text{SC V} & 1 & 0.5 & 0 & 0 & -0.5 & -1 \\
\text{CBg V} & 0.5 & 1 & 0.5 & 0 & 0 & -0.5 \\
\end{array} \]
Model behavior

Simulation example: Conjugate versus dissociate gaze and head movements

- Target$_S$
- Head$_S$
- Gaze$_S$
- Eye$_H$
- Parallel
- Nonparallel

\[
\begin{array}{c}
\text{Target}_S & \text{Head}_S & \text{Gaze}_S & \text{Eye}_H & \text{Parallel} & \text{Nonparallel} \\
\end{array}
\]

\[
\begin{array}{c}
\text{V [deg]} & \text{H [deg]} & \text{Time [sec]} \\
0 & -40 & 0 \\
10 & -30 & 0.25 \\
20 & -20 & 0.5 \\
30 & -10 & 0.75 \\
40 & 0 & 1 \\
\end{array}
\]
Model behavior

Simulation example: Conjugate versus dissociate gaze and head movements

![Graph showing head movements](image-url)
Model behavior
Simulation example: Conjugate versus dissociate gaze and head movements

![Diagrams showing conjugate and dissociate gaze and head movements.](image-url)
Model behavior

Simulation example: EBN gain 3 times bigger horizontally

\[ \dot{H}^* \]

\[ \Delta G \]

\[ \Delta H \]

CBLM (Feedback)

SC (Drive)

Head independent

\[ \dot{H}^* \]

Premotor brainstem

Spinal cord

VOR

EYE Plant

HEAD Plant

SCC

CAP
Model behavior

Simulation example: EBN gain 3 times bigger horizontally

Target \( T \)
Head \( H \)
Gaze \( G \)
Eye \( E \)
\[ E_H = E_V \]
\[ E_H > E_V \]
Model behavior

Simulation example: EBN gain 3 times bigger horizontally
Model behavior

Simulation example: EBN gain 3 times bigger horizontally

![Diagram](image-url)
Take home message

Summary

- Gaze saccade model based on two controllers:
  1. Gaze feedback controller: corrects gaze trajectory with quick eye movement
  2. Head “static position controller”: allows distinct goals for gaze and head trajectories.
Take home message

Summary

- Gaze saccade model based on two controllers:
  1. Gaze feedback controller: corrects gaze trajectory with quick eye movement
  2. Head “static position controller”: allows distinct goals for gaze and head trajectories.

Conclusion

- Model based on anatomy
  - Add constraints
  - Clinically more relevant
- Eyes are not independent but serve gaze
Further...

[Diagram of gaze model with nodes labeled as follows:
- CBLM (Feedback)
- SC (Drive)
- Head independent estimator
- Premotor brainstem
- Spinal cord
- VOR
- EYE Plant
- HEAD Plant
- SCC
- CAP

Symbols used in the diagram include:
- $\dot{H}^*$
- $\dot{E}^*$
- $\Delta G$
- $\Delta H$

Additional notes include:
- Pierre Daye (UCLouvain)
- 2D gaze model
- Sept 23th, 2009}
Further ⇒ Head-unrestrained tracking
Further ⇒ Saccade-pursuit interaction

Modified saccadic model
Further $\Rightarrow$ Saccade-pursuit interaction

Modified saccadic model
Further ⇒ Saccade-pursuit interaction

Simulation

Target
Head
Gaze
Eye

Time [sec] 0 0.25 0.5 0.75
V [deg] 15 10 5 0

Time [sec] 0 0.25 0.5 0.75
V [deg/s] 75 50 25 0

Time [sec] 0 0.25 0.5 0.75
H [deg] 10 5 0 -5

Time [sec] 0 0.25 0.5 0.75
H [deg/s] 100 50 0 -50

Time [sec] 0 0.25 0.5 0.75
Everyday life movements versus movements in the lab

More “realistic” movements