The brain accounts for 3D eye and head kinematics in the visuomotor transformation of velocity signals in manual tracking

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How to catch the ball?
How to catch the ball?

→ People think:

It is not an easy task but it is not too difficult
How to catch the ball?

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→ However, what if I ask you to design a robot to carry out such a task?
How to catch the ball?

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→ However, what if I ask you to design a robot to carry out such a task?

→ The brain must carry out a fast and complex sensorimotor transformation
Outline

- The feedforward control of visually guided arm movements
- Visuomotor transformation for manual tracking
  - Static case: eye and head are static
  - Dynamic case: the eye is moving
- Conclusion and future work
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The feedforward control of visually guided arm movements

For the player, the variables of interest are:

- the target position and velocity
- his left hand’s position and velocity
How does the brain get access to these variables?
Visual information about the target, through the retina
Visual+proprioceptive information about the hand, through the retina and proprioceptive sensors
Variables are encoded by the brain in a retinotopic reference frame.

→ Proprioceptive and visual cues about hand variables are combined and the resulting estimation is represented in retinal coordinates.
The next step for the brain is to **transform** this **sensory** information into a **motor plan**

→ **Motor plan** = desired movement vector for the hand
The **motor plan** is specified in a reference frame attached to the shoulder.

→ Insertion point of the arm is the shoulder.
The brain uses an **internal model** to carry out the transformation.
At the end, arm’s **muscles** move the arm

→ Therefore, specifying the motor plan is not the last step
Therefore, the brain must transform the **motor plan** into a set of **motor commands** sent to the arm’s muscles.

This last step is also carried out through an internal model, called the **inverse model**.
Therefore, the brain must transform the motor plan into a set of motor commands sent to the arm’s muscles.

This last step is also carried out through an internal model, called the inverse model.
That is for the **feedforward** control…

Now a few words about **feedback**…
Sensory feedback is provided with an important physiological delay.
Internal feedback is provided by sending a copy of the motor command sent to the muscles...
Internal and sensory feedback are combined to produce an **error signal** used to correct the movement.
Here we only investigate the **feedforward** part of the control of the arm movement.
We are interested in the **visuomotor transformation** step.
How complex is the visuomotor transformation? Are extra-retinal signals taken into account?
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retinal (eye) coordinates  screen (space) coordinates

Retinal projection

PT: moving

PT: Pointing Target
F: Fixation
Retinal velocity error and motor plan are **aligned**

- Retinal (eye) coordinates
- Screen (space) coordinates

**Retinal projection**

- PT: Pointing Target
- F: Fixation

PT: moving
But what happens if your **head is tilted** towards your left shoulder?

Head roll = 30deg
The projection of the velocity vector is also tilted onto the retina.

retinal (eye) coordinates  screen (space) coordinates

Retinal projection

Head roll = 30deg
Retinal velocity error and motor plan are no longer aligned
If the brain **only** uses **retinal information** as input, there will be a large **error** in the **initial arm direction**.

The initial direction of the arm has an error = 30deg
If the brain **also** uses **3D head position** signal with an internal model of the **eye-head-shoulder** geometry, there will be **no error** in the **initial arm direction**.

→ The **initial direction of the arm** has an error = **0deg**
Visuomotor transformation: **Hypothesis 1**

The brain only takes the **retinal signal** into account.
Visuomotor transformation: **Hypothesis 2**

The brain accounts for the **3D eye and head position** in addition to the retinal signal, combining them using an **internal model of the eye-head-shoulder geometry**.

![Diagram showing full compensation (3D)](image)
Visuomotor transformation: Two extreme hypotheses

No compensation (retinal prediction)

- retinal velocity
- direct transformation
- motor plan for the arm

Full compensation (3D)

- retinal velocity
- 3D eye position
- 3D head position
- 3D transformation
- motor plan for the arm
Visuomotor transformation: Two extreme hypotheses

Hand position and velocity: $H, \dot{H}$
Target position and velocity: $T, \dot{T}$

Initial conditions

Retinal coordinates

Internal model

Visuomotor transformation

Extra-retinal signals:
- 3D eye position?
- 3D head position?

Hand motor plan

Shoulder coordinates

Inverse model

Internal model

Motor command for the arm's muscles

Arm + body + environment
Geometric model: we consider the **eye-head-shoulder** system as a **rigid body system**

→ **Input** (target velocity) to the visuomotor transformation model are encoded in **retinal coordinates**, so in a reference frame attached to the eye.
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- Therefore, the brain must perform a *reference frame transformation*. It should take into account:
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  - 3D eye-in-head rotation (describing eye orientation)
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  - translation between rotation centers of the eye and head.
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  - translation between rotation centers of the eye and head.

→ The model is described using screw motion theory, under the form of dual quaternions.
Why do we use dual quaternions?

→ They easily represent rotations and translations.
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\[
PT^{EE} = R_{EH} PT^{EH} R_{EH}^*
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\[ = R_{EH} T_{HE} P_{TH} T_{HE} R_{EH}^* \]
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\[ P^{EE} = R_{EH} P^{EH} R_{EH}^* \]

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\[ = R_{EH} T_{HE} R_{HS} P^{HS} R_{HS}^* T_{HE} R_{EH}^* \]
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\[
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\]
\[
= R_{EH} T_{HE} \mathbf{PT}_{HH} T_{HE} R_{EH}^*
\]
\[
= R_{EH} T_{HE} R_{HS} \mathbf{PT}_{HS} R_{HS}^* T_{HE} R_{EH}^*
\]
\[
= R_{EH} T_{HE} R_{HS} T_{SH} \mathbf{PT}_{SS} T_{SH} R_{HS}^* T_{HE} R_{EH}^*
\]
Experimental paradigm: HEAD ROLL experiment

Head roll
Experimental paradigm: HEAD ROLL experiment

- GT: Gaze Target
- Head roll
- Gaze fixation
- Time
Experimental paradigm: HEAD ROLL experiment

- **PT**: Pointing Target
- **GT**: Gaze Target

- Head roll
- Gaze fixation
- Initial pointing position

Time
Experimental paradigm: HEAD ROLL experiment
Typical trial: HEAD ROLL experiment
Typical trial: HEAD ROLL experiment

- Head position (deg)
- Eye position (deg)
- Pointing position (deg)
- Pointing velocity (deg/s)

 PT onset

 Graphs showing changes in head and eye position over time, with different orientations indicated by blue (Horizontal), yellow (Torsion), and black (Vertical). A separate graph displays pointing position (deg) and horizontal position (deg) with markers for PT and GT.
PT starts moving with a 10deg orientation
3D eye and head positions are constant
Initial arm direction if predicted using only retinal information
The measured initial arm direction is close to the PT direction.
Mean initial arm directions follow PT trajectories and not the directions predicted using retinal hypothesis.
Quantifying the results

Measuring the initial arm direction, $\text{dir}_{\text{obs}}$, for each trial
Quantifying the results

First we compute the **arm movement onset**
Quantifying the results

Then, the initial arm direction, $\text{dir}_{\text{obs}}$, is measured over the first 100ms after arm movement onset.

Below 100ms, only the feedforward component is in play since physiological delay in sensory feedback is higher than 100ms.
Compensation index

→ Then, the initial arm direction, $\text{dir}_{\text{obs}}$, is measured over the first 100ms after arm movement onset.

→ compensation index:

\[
\text{compensation} = \frac{\text{dir}_{\text{obs}} - \text{dir}_{\text{retinal}}}{\text{dir}_{\text{PT}} - \text{dir}_{\text{retinal}}} = \frac{\text{observed correction}}{\text{predicted 3D correction}}
\]
If the brain does not take into account the head roll, then there is **no correction** and **slope = 0**
If the brain perfectly compensates for the head roll, then there is **full correction** and slope = 1.
Data across 7 subjects
Head roll is taken into account by the brain

Full compensation

$y = -0.18 + 1.08x$

Observed correction (deg)

Predicted 3D correction (deg)

No compensation
All subjects compensate for the head roll
All subjects compensate for the head roll and some subjects “overcompensate”
What are the possible explanations for this overcompensation?
When we roll our head by 30deg…

retinal (eye) coordinates  screen (space) coordinates

Retinal projection Head roll = 30deg
When we roll our head by 30deg... **Our eyes rotate in the opposite direction**, around the line of sight by about 3deg. This effect is known as the static ocular counter-roll (OCR).

\[
\text{ocular counter-roll} \\
\text{OCR} = 3\text{deg}
\]
When we roll our head by 30deg… Our eyes rotate in the opposite direction, around the line of sight by about 3deg. This effect is known as the static ocular counter-roll (OCR).

\[
\text{OCR} = 3\text{deg}
\]

\[
\alpha = 27\text{deg}
\]
The observed **overcompensation may** due to the fact that head roll but not OCR is taken into account.

**Ocular counter-roll**

OCR = 3deg

**Head roll**

Head roll = 30deg  
OCR = 3deg  
\[ \Rightarrow \alpha = 27\text{deg} \]
The observed overcompensation may be due to the fact that head roll but not OCR is taken into account.

For example, the brain would compensate for 30deg while he should have only compensated for 27deg.

- retinal (eye) coordinates
- screen (space) coordinates

**Ocular Counter-Roll (OCR)**

OCR = 3deg

Retinal projection

Head roll = 30deg
OCR = 3deg

\[ \Rightarrow \alpha = 27 \text{deg} \]
This hypothesis suggests that the brain does not use an OCR signal in the visuomotor transformation.

For example, the brain would compensate for 30deg while it should have only compensated for 27deg.

\[ \text{The brain has an accurate internal representation of the head roll angle.} \]

\[ \text{The brain does not have a measure of the ocular counter-roll for the visuomotor transformation.} \]
But alternative hypotheses exist…
But alternative hypotheses exist…

→ Maybe the internal **head roll signal is biased** (maybe is it also the case for the OCR angle).
But alternative hypotheses exist...

- Maybe the internal **head roll signal is biased** (maybe is it also the case for the OCR angle).
- Maybe the **internal model** for the transformation has accurate inputs but is **miscalibrated**.
Does the brain take into account the OCR angle?

Multiple linear regression:

\[
\text{observed correction} = c_1 \cdot \text{head roll} + c_2 \cdot \text{OCR}
\]
Does the brain take into account the OCR angle?

$\rightarrow$ Multiple linear regression:

$$\text{observed correction} = c_1 \cdot \text{head roll} + c_2 \cdot \text{OCR}$$

$\rightarrow$ Results:
- $c_2$ is different from 0 for each subject
Does the brain take into account the OCR angle?

Multiple linear regression:

\[
\text{observed correction} = c_1 \cdot \text{head roll} + c_2 \cdot \text{OCR}
\]

Results:
- \(c_2\) is different from 0 for each subject
- The multiple regression has a correlation coefficient significantly greater than the correlation coefficient of the simple regression using head roll only.
Does the brain take into account the OCR angle?

\[ \text{Full compensation (3D)} \]

\[ \text{observed correction} = c_1 \cdot \text{head roll} + c_2 \cdot \text{OCR} \]

\[ \rightarrow \text{Results:} \]
- \( c_2 \) is different from 0 for each subject
- The multiple regression has a correlation coefficient significantly greater than the correlation coefficient of the simple regression using head roll only.

\[ \rightarrow \text{The OCR angle is taken into account in the visuomotor transformation, at least partially} \]
Oblique gaze: what do we expect?

screen (space) coordinates
The velocity vector is **slightly tilted** onto the retina.
Direction predicted according to the retinal hypothesis

retinal (eye) coordinates  screen (space) coordinates
The error in direction is about 5 deg for a 30 deg eccentricity
Results: **3D eye position** is (partially) taken into account in the visuomotor transformation

\[ y = -0.93 + 0.86x \]
All subjects (partially) compensate for the 3D eye position except two subjects.
Summary: Static case: eye and head are static

→ Visuomotor transformation for manual tracking in a static eye-head-shoulder configuration

Full compensation (3D)

- retinal velocity
- 3D eye position
- 3D head position
- 3D transformation
- motor plan for the arm
Summary: Static case: eye and head are static

→ Visuomotor transformation for manual tracking in a static eye-head-shoulder configuration

Full compensation (3D)

retinal velocity → 3D transformation → motor plan for the arm

3D eye position, 3D head position

→ The brain has an internal model of the 3D eye-head-shoulder geometry and uses 3D eye and head position signals
Summary: Static case: eye and head are static

→ Visuomotor transformation for manual tracking in a static eye-head-shoulder configuration

The brain has an internal model of the 3D eye-head-shoulder geometry and uses 3D eye and head position signals

→ However, compensation is sometimes not perfect due to:
  - miscalibrated model?
  - biased and noisy internal 3D eye/head position signals
Outline

- The feedforward control of visually guided arm movements
- Visuomotor transformation for manual tracking
  - Static case: eye and head are static
  - Dynamic case: the eye is moving
- Conclusion and future work
A visually guided manual tracking task...

screen (space) coordinates

PT: moving

GT: static

PT: Pointing Target
GT: GazeTarget
Retinal error and motor plan are aligned.
But what if the **eye** is itself **moving**?
But what if the **eye** is itself **moving**?

\[ \alpha_g = \text{GT direction} \]
\[ \alpha_p = \text{PT direction} \]
\[ \alpha = \alpha_g - \alpha_p = 90 \text{deg} \]
Retinal error and motor plan are no longer aligned.

\[ \alpha_g = \text{GT direction} \]
\[ \alpha_p = \text{PT direction} \]
\[ \alpha = \alpha_g - \alpha_p = 90\,\text{deg} \]
If the brain only takes into account the *retinal* information, there is a **large error** in the initial arm direction.

\[ \text{Error in initial arm direction} = 45 \text{ degrees} \]
If **eye velocity** is accounted for, there is **no error** in initial arm direction.

\[ \alpha_g = \text{GT direction} \]
\[ \alpha_p = \text{PT direction} \]
\[ \alpha_{predret} = \text{retinal predicted direction} \]

\[ \rightarrow \text{Error in initial arm direction} = 0 \text{ degrees} \]
Visuomotor transformation: **Hypothesis 1**

The brain only takes the **retinal signal** into account.

![Diagram](image)

- **No compensation (retinal prediction)**
- Direct transformation
- Motor plan for the arm

**Screen (space) coordinates**

- $\alpha_g$ = GT direction
- $\alpha_p$ = PT direction

**Retinal (eye) coordinates**

- $\alpha_{pred}$ = retinal predicted direction

**GT velocity = PT velocity**
Visuomotor transformation: **Hypothesis 2**

The brain accounts for the **3D eye and head position and velocity signals** in addition to the retinal signal, combining them using an **internal model of the eye-head-shoulder kinematics**.
Visuomotor transformation: **Two hypotheses**

**No compensation (retinal prediction)**

- Retinal velocity
- Direct transformation
- Motor plan for the arm

**Full compensation (3D)**

- Retinal velocity
- 3D transformation
- 3D eye: position, velocity
- 3D head: position, velocity
- Motor plan for the arm
Kinematic model: we still consider the eye-head-shoulder system as a rigid body system

- The same formalism is used as before.
- Time-varying eye-in-head rotation
  - Dual quaternions derivatives are needed.
The error in initial arm direction depends on the ratio between GT velocity and PT velocity.

\[ \alpha_g = \text{GT direction} \]
\[ \alpha_p = \text{PT direction} \]
\[ \alpha = \alpha_g - \alpha_p = 90 \text{deg} \]
When both targets have **equal velocities**, the errors depend **linearly** on the difference of targets directions.
When GT velocity < PT velocity, the error is lower but depends **non-linearly** on the difference of targets directions.
When GT velocity > PT velocity, the error is greater and depends \textbf{non-linearly} on the difference of targets directions.
When GT velocity > PT velocity, the error is greater and depends **non-linearly** on the difference of targets directions.

→ The error is greater and more sensitive when the difference in targets directions is low.
Experimental paradigm

- PT: Pointing Target

![Initial pointing](image)
Experimental paradigm

- PT: Pointing Target
- GT: Gaze Target

Initial pointing

Initial gaze fixation

Time
Experimental paradigm

- PT: Pointing Target
- GT: GazeTarget

Initial pointing

Initial gaze fixation

Smooth pursuit only
random time between 500 and 1000ms
GT velocity = 10, 20 or 30 deg/s
Experimental paradigm

- **PT**: Pointing Target
- **GT**: Gaze Target

**Initial pointing**

**Initial gaze fixation**

**Smooth pursuit only**
- Random time between 500 and 1000ms
- GT velocity = 10, 20, or 30 deg/s

**Manual tracking + smooth pursuit**
- GT and PT move together, PT velocity = 20 deg/s

\[ \alpha_g = \text{GT direction} \]
\[ \alpha_p = \text{PT direction} \]
Typical trial
Typical trial

- Vertical position (deg)
- Horizontal position (deg)
Typical trial

- Vertical position (deg)
- Horizontal position (deg)

- GT
- PT

- Initial gaze fixation
Typical trial

- Vertical position (deg)
- Horizontal position (deg)

GT: eye trajectory
PT: initial gaze fixation
Typical trial

![Graph showing typical trial](image)

- **Vertical position (deg)**
- **Horizontal position (deg)**

- **GT**
- **PT**
- **Eye trajectory**
- **Initial gaze fixation**

- **Smooth pursuit**
- **Saccade**
Typical trial
Typical trial

- Vertical position (deg)
- Horizontal position (deg)

- Smooth pursuit
- Saccade

- Initial pointing
- Initial gaze fixation
- Eye trajectory
- 300ms-period after PT onset
Typical trial

Graph showing eye trajectory, initial pointing, retinal prediction, and initial gaze fixation. The graph plots vertical position (deg) against horizontal position (deg). The 300ms-period after PT onset is highlighted.
Typical trial

- Vertical position (deg)
- Horizontal position (deg)
- Arm trajectory in the 200ms-period after arm onset
- Retinal prediction
- Initial gaze fixation
- Initial pointing
- Eye trajectory
- Smooth pursuit
- Saccade

300ms-period after PT onset
Typical trial

- Target blanking period
- Pointing trajectory
- Retinal prediction
- Initial pointing
- Initial gaze fixation
- Eye trajectory:
  - Smooth pursuit
  - Saccade

GT

Eye

300ms-period after PT onset
Typical trial
If no correction, slope = 0
If full 3D compensation, slope = 1
Data points across 8 subjects

Observed correction (deg) vs. Predicted 3D correction (deg)

- Data points
- Full compensation line
- No compensation line

Across 8 subjects
Eye velocity is taken into account

\[
y = -12 + 0.87 \times x \\
R = 0.86
\]
All subjects slightly under-compensate
Summary: Dynamic case: the eye is moving

→ Visuomotor transformation for manual tracking in a **dynamic** eye-head-shoulder configuration

![Diagram: Full compensation (3D)]
Summary: Dynamic case: the eye is moving

→ Visuomotor transformation for manual tracking in a dynamic eye-head-shoulder configuration.

![Diagram of Full compensation (3D)]

→ The brain has an internal model of the 3D eye-head-shoulder kinematics and uses 3D eye velocity signal.
Summary: Dynamic case: the eye is moving

→ Visuomotor transformation for manual tracking in a dynamic eye-head-shoulder configuration.

![Diagram: Full compensation (3D)]

→ The brain has an internal model of the 3D eye-head-shoulder kinematics and uses 3D eye velocity signal.

→ The compensation is between 80 and 95%. This may be due to:
  - a miscalibrated model
  - a biased internal 3D eye velocity signal
Conclusion

• The brain makes use of extra-retinal signals:
  - 3D eye position
  - 3D head position
  - eye velocity
in the visuomotor transformation of velocity signals for manual tracking, accounting for the 3D eye-head-shoulder kinematics.
Conclusion

• The brain makes use of extra-retinal signals:
  - 3D eye position
  - 3D head position
  - eye velocity

  in the visuomotor transformation of velocity signals for manual tracking, accounting for the 3D eye-head-shoulder kinematics.

• The compensation is sometimes partial, or too great. It may be due to several factors:
  - a miscalibrated internal kinematic model?
  - biased and noisy internal extra-retinal signals?
  - other?
Future work

• How can this transformation be performed by a biologically plausible neural network?
  → Explain neurophysiological findings
  → Predict neuronal properties

• extend the model to binocular information and the depth side of reaching/tracking
Thank you for your attention