Visuomotor velocity transformations for visually guided manual tracking

G. Leclercq[1], G. Blohm[2] and P. Lefèvre[1]

[1] CESAME & Lab. Neurophysiology, Université Catholique de Louvain, Louvain-la-Neuve, Belgium
[2] Centre for Neuroscience Studies, Queen's University, Kingston, Canada

Abstract— **To achieve accurate visually guided arm movements the brain transforms visual input into appropriate motor commands for the arm. For reaches towards static targets this transformation accounts for the complete 3D eye-head-shoulder geometry [1]. However, position and velocity signals are processed by different neural pathways. Therefore, we ask whether a similar visuomotor transformation is also performed for velocity signals. To address this question, we designed a model describing the complete visuomotor transformation geometry for pointing, accounting for 3D eye-in-head and head-on-shoulder rotations and translations. The model predicted compensation for (1) head roll and resulting counter-roll eye movements and (2) for false ocular torsion generated by a misalignment between the retinal and spatial coordinates during oblique gaze positions. We tested these predictions on human subjects that performed manual tracking movements towards moving targets in darkness under different eye and head positions. To test prediction 1, subjects first had to roll their head towards either shoulder. Then, they pointed to the central target, which started moving 1s later either to the left or right with an angular vertical component of -10, 0 or 10deg. Subjects had to track the moving target with their hand while maintaining fixation. Testing prediction 2 was similar, but now the head was maintained in an upright position and subjects instead fixated oblique targets while the same tracking task was carried out. We measured eye, hand and head movements and computed arm velocity during the open-loop period (first 200ms after movement onset). This initial movement direction was then compared to the model predictions to check whether the 3D eye-head-shoulder geometry was fully, partially or not at all taken into account in the visuomotor transformation. First results suggest that for manual tracking movements, the brain accounts for this complete geometry.**

Keywords— **arm, head, eye, velocity, pointing, geometry**

I. INTRODUCTION

Visually guided arm movements such as reaching or pointing to an object are ordinary actions in our everyday life. Even if such movements seem easy to perform, they are the result of a complex sensorimotor transformation carried out in the brain. To achieve accurate visually-guided arm movements, humans combine feed-forward information with visual and/or proprioceptive feedback about the movement. The feed-forward part tackles the geometry of the visuomotor transformation, that is, the brain needs to transform the retinal sensory input into an appropriate motor command for the arm (see [2]) before initiating the movement.

It has been shown that such a transformation accounts for the complete 3-dimensional (3D) eye-head-shoulder geometry in the case of reaching movements towards static targets [1]. To do so, in addition to the retinal position information the brain takes extraretinal signals into account providing current head and eye position.

It is known that sensory retinal position and velocity signals are processed by different neural circuits in the brain [3]. Therefore, velocity signals have to undergo a separate geometrical transformation than position signals. Here, we asked whether the visuomotor transformation of velocity signals also accounted for the 3D eye-head-shoulder linkage geometry in the arm movements framework. To answer this question, we designed a manual tracking experiment where we varied eye and head positions. We compared experimental results with several theoretical predictions: the *complete prediction* (CP), taking into account 3D eye and head rotations, and the *retinal prediction* (RP), using only the retinal velocity information to generate the motor plan.

II. METHODS

A. Experimental Setup

Seven right-handed healthy human subjects (aged 23-43 years, 4 naive) participated in the experiments after giving informed consent. All subjects had normal or corrected-to-normal vision and were without any known sensory or motor anomalies. All procedures were conducted with approval of the Université catholique de Louvain Ethics Committee.

Subjects were seated in complete darkness. They faced a 1-m distant translucent flat screen which covered about ±40 deg of their visual field in both vertical and horizontal directions. Two different targets – a green and a red 0.2° LASER spot – were back-projected onto the screen using two pairs of mirror galvanometers. A dedicated real-time computer running LabViewRT (National Instruments) controlled illumination and position of both targets with a refresh rate of 1000Hz. This computer also controlled the illumination of a green LED attached to the tip of the subjects' index finger.

Subjects' left eye was patched during the experiment to avoid switching the dominant eye when pointing to different hemi-fields [4]. Right eye movements were recorded (200Hz) using a head-mounted Chronos 3D video eye tracking device. Arm- and head-in-space positions were measured (200Hz) using a Codamotion active infrared marker tracking device.

B. Paradigms

A manual tracking task was designed to assess if subjects accounted for the 3D eye-head-shoulder geometry in the visuomotor transformation. We tested separately the effect of head roll angle and gaze direction on the direction of manual tracking initiation. To this end, two paradigms were used: the *head-roll* paradigm and the *gaze* paradigm.

During a *head-roll* trial (Figure 1A), subjects first rolled their head in the direction indicated by a line displayed on the screen, i.e. toward left shoulder, right shoulder or upright position. After fixating their gaze on the central target location (red cross), subjects were required to align the finger LED with the pointing target (PT, green circle) also located at the screen center. The finger LED was then switched off in order to prevent from any visual feedback of the arm. At this time, PT started to move and subjects were asked to track PT with their finger. PT moved for 1200 ms at constant velocity along a straight line in a given direction. After 300ms, the target was extinguished for 450ms (see Figure 2) so that hand movement onset generally occurred in the absence of the target. The trial ended with a 500 ms period during which subjects maintained pointing towards the static final pointing target.

Both PT velocity and direction varied randomly across trials. PT velocity changed between 10, 20 and 30deg/s. PT direction was either to the left or to the right with an angular vertical component of -10, 0 or 10deg. This small vertical component prevented subjects from making stereotyped movements after some repetitions. We used a bite-bar attached to the Chronos eye tracker to ensure that the helmet did not move on the head during a session.

In the *gaze* paradigm (Figure 1B), subjects started with pointing to the center of the screen. Then, a gaze fixation target appeared on one of the two upper diagonals with an eccentricity of 0, 15 or 30deg. Subjects were required to orient their gaze to the gaze fixation target within a 500ms period and to maintain the gaze fixated until the end of the trial. The remaining part of the trial was similar to the *head-roll* paradigm. Subjects tracked the moving target with their hand (target movement was the same as for head roll trials). PT velocity was 20deg/s for all trials and did not vary across trials. In the *gaze* paradigm, a chin-rest was used to maintain the head in an upright position.

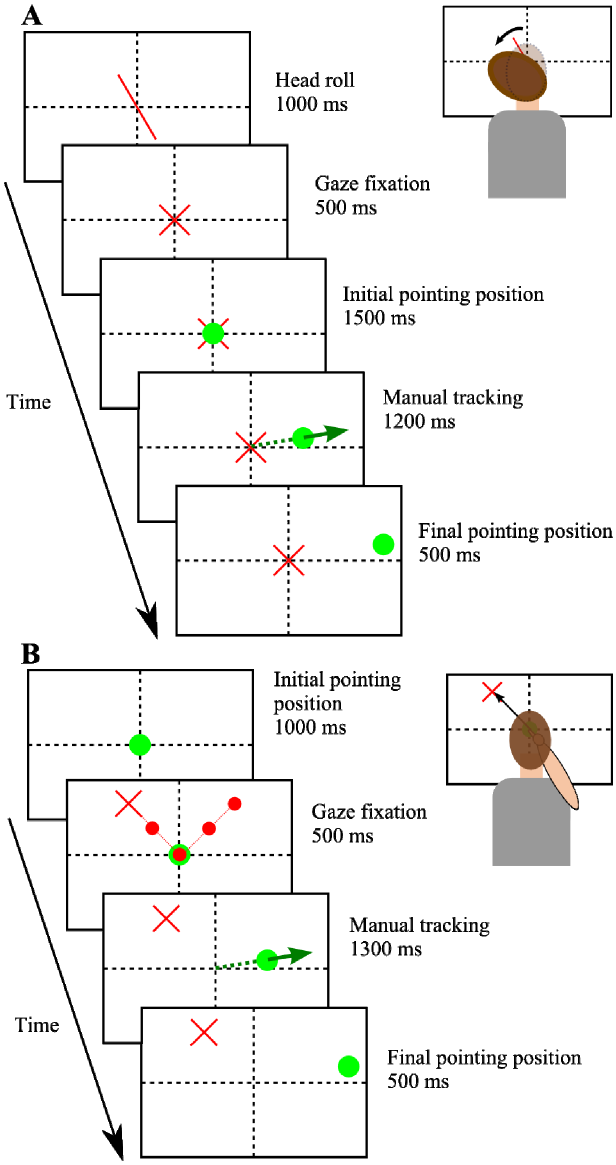

Fig. 1 Experimental paradigms **A** *Head-roll trial.* After rolling the head (towards left shoulder, right shoulder or upright), gaze is maintained at screen center and subjects point to the screen center. Pointing target moved for 1200 ms at 10, 20 or 30deg/s to the right or left with an angular vertical component of -10, 0 or 10deg, before reaching a final static position for 500ms. **B** *Gaze trial.* After pointing to the screen center, subjects orient their gaze on one of the five targets (red circles, red cross is the gaze target for this trial) located on the two upper diagonals at 0, 15 or 30deg eccentricity. Pointing target moved for 1300ms at 20deg/s in one of the six directions (see text).

Experimental sessions started with a gaze calibration block where subjects fixated different known positions without moving the head. A so-called pointing calibration block followed, where subjects had to look at and point their arm towards different known positions. Three or four blocks of 30 trials were then carried out before repeating the calibration procedure and so on. One session lasted 50 minutes maximum. In the *gaze* paradigm, there were 5 different gaze positions and 6 different PT directions, leading to 30 conditions. In the *head-roll* paradigm, there were 6 different directions, 3 different indications of head roll and 3 different velocities, resulting in 54 conditions. Overall, each condition was repeated ten times.

C. Data analysis

Collected data (eye, target, head and arm position) were stored on a hard-disc for off-line analysis which was carried out with MATLAB (Mathworks, Inc.). Position signals were low-pass filtered using a zero-phase digital filter (autoregressive forward-backward filter, cutoff frequency: 50Hz). Velocity signals were estimated from position signals by using a central difference algorithm. Eye torsion was extracted using the IRIS software (Chronos Vision, Germany). Users define several segments on the iris and the software uses a cross-correlation algorithm to estimate ocular torsion (see [5]).

All trials were visually inspected. For each trial, we selected the torsion estimation by taking the most accurate torsion measurement (as indicated by the R^2-value) which was consistent with the predicted torsion given by Listing's law. Trials where people did not maintain gaze fixation during manual tracking were discarded from the analysis. Onset of the arm movement was automatically detected by a velocity threshold of 3deg/s and manually corrected if necessary.

For each trial, we computed the initial arm movement direction. The initial arm movement direction was estimated from the first 200ms after movement onset. This short time period prevented proprioceptive feedback from influencing the hand movement (there was no visual feedback of the arm). Initial arm movement direction was determined (i) from the ratio between the mean vertical arm velocity and the mean horizontal arm velocity, (ii) or from the ratio between the mean vertical arm acceleration and the mean horizontal arm acceleration over this 200ms period.

III. RESULTS

A typical trial in the *gaze* paradigm is illustrated in Figure 2. Subject tracked PT while maintaining fixation. Subjects tended to overshoot the final PT position in darkness. Trials where subjects moved their gaze during or after PT movement onset were removed from the analysis. Indeed, subjects sometimes pursued the PT instead of maintaining fixation, especially during the first trials. Those trials were removed from the analysis. Subjects typically started their manual tracking movement just before or during the PT occlusion period (grey area on Figure 2). Subjects reported that they were generally unaware of target movement direction which prevented them to make memorized, stereotyped movements in response to perceived PT direction.

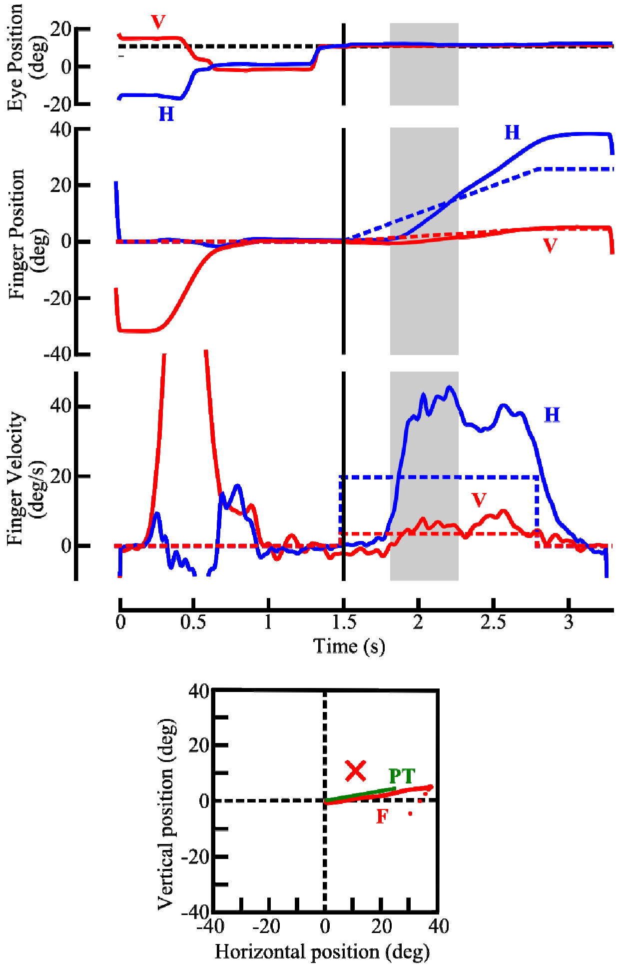

Fig. 2 Typical trial in the *gaze* paradigm. Panel **A** describes the evolution of the vertical (**V**) and horizontal (**H**) components of eye position, finger position and finger velocity during a trial. Eye and finger position and velocity measurements are shown in solid lines while target position and velocity is represented by dashed lines. At 1.5 second, a thick vertical black line represents the movement onset of the pointing target (**PT**). The grey rectangle shows the period where **PT** is not visible. Panel **B** represents pointing target (**PT)** and finger (**F**) trajectory. Gaze fixation is represented by the red cross.

Figure 3 illustrates the need for a visuomotor transformation accounting for the geometry in the oblique gaze case and in the head-roll case. Indeed, in the oblique gaze situation, the projection of PT velocity vector on the retina is slightly tilted. The *Complete Prediction* (CP) model corrects this tilt while the *Retinal Prediction* (RP) model directly maps the tilted retinal velocity to the motor command of the arm. In the head-roll case, the retinal velocity tilt is quite important, resulting from the head roll angle and ocular counter-roll.

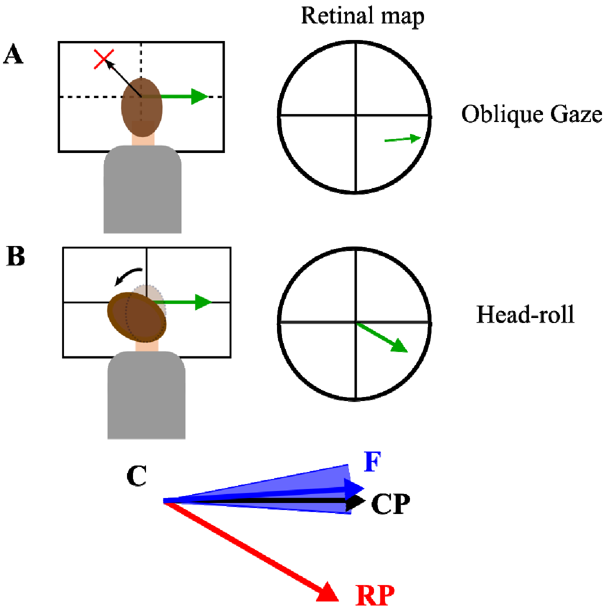

Fig. 3 Model predictions for velocity visuomotor transformation. Left part of Panel **A** describes the *gaze* paradigm where subject is fixating the red cross at 30 deg oblique eccentricity. The green arrow represents the PT velocity vector in space. In the retinal projection (right), the velocity vector is slightly tilted counter-clockwise due to the eccentric gaze and non-linear projections. Panel **B** shows the *roll* paradigm. Due to the head-roll towards the left shoulder, the retinal velocity vector is tilted on the retina. Panel **C** shows model predictions in the case described in panel B. Black arrow represents the complete prediction (**CP**) taking into account the complete 3D eye-head geometry (here, head roll is taken into account). The red arrow shows the retinal prediction (**RP**), which uses the retinal velocity as a motor command for the arm. The blue arrow represents the mean finger (**F**) movement direction of one subject. The light blue area represents the mean ± standard deviation in the measured direction.

Figure 3C shows an example of subject behavior in the head roll case. RP and CP predictions are represented by the red and black arrows respectively. Subject's measured mean ± standard deviation of the movement direction (in blue) is clearly overlapping with the CP prediction and is significantly different from the RP prediction.

IV. CONCLUSION

We investigated if the brain achieves a complete visuomotor transformation for velocity signals in a manual tracking task, accounting for the 3D eye-head-shoulder geometry. Two experiments were designed to assess the different model predictions: a direct visuomotor transformation based on the retinal information only, or a complete visuomotor transformation taking into account extraretinal position signals. From first results, it appears that subjects indeed take the complete geometry into account when performing a manual tracking task. Further analysis is required to confirm these results.

ACKNOWLEDGMENT

This work was supported by Marie Curie (EU), FNRS (Belgium), IAP/DYSCO and PRODEX (SSTC, Belgium), ESA (EU), ARC (UCLouvain, Belgium), NSERC (Canada), Botterell Fund (Queen's University, Canada)

REFERENCES

1. Blohm G, Crawford JD (2007) Computations for geometrically accurate visually guided reaching in 3-D space. Journal of Vision, 7(5):4, 1-22, http://journalofvision.org/7/5/4/, doi:10.1167/7.5.4.
2. Crawford JD, Medendorp WP, Marotta JJ (2004) Spatial transformations for eye-hand coordination, Journal of Neurophysiology, 92, 10-19 doi:10.1152/jn.00117.2004 0022-3077/04
3. Krauzlis RJ (2005). The control of voluntary eye movements: new perspectives. Neuroscientist 11, 124–137
4. Khan AZ, Crawford JD (2003) Coordinating one hand with two eyes: optimizing for field of view in a pointing task. Vision Research, 43(4), 409-417, doi:10.1016/S0042-6989(02)00569-2
5. Schreiber K, Haslwanter T (2004), Improving calibration of 3-d video oculography systems, IEEE Trans. Biomed. Eng. 51(4), 676-679, 10.1109/TBME.2003.821025

- Author: Guillaume Leclercq
- Institute: CESAME
- Street: Avenue Georges Lemaître, 4
- City: Louvain-la-Neuve
- Country: Belgium
- Email: guillaume.leclercq@uclouvain.be