Compensation for smooth eye and head movements by gaze saccades during head-unrestrained tracking

P. Daye[1,2], G. Blohm[1,3] and P. Lefèvre[1,2]

[1] Center for Systems Engineering and Applied Mechanics (CESAME), Université catholique de Louvain, Belgium
[2] Laboratory of Neurophysiology, Université catholique de Louvain, Belgium
[3] Center for Neurosciences Studies, Queen's University, Kingston, Ontario, Canada

Abstract— **Gaze orientation is generally performed using combined eye and head movements. It has been shown in head fixed conditions that smooth eye movements occurring during the saccade latency period are compensated for if the brain has enough time to integrate eye velocity [2,3,4]. Here, we asked whether this was the same when the head was free to move.**

Subjects sat in front of a 1-m distant tangential screen. They were instructed to pursue a sinusoidal target (Frequency [0.6 to 1.2 Hz]) moving along a straight line in 2D (Orientation [0 to 360°] and amplitude [20 to 25°] randomly chosen). 2.2-3.8s after target motion onset, a second target was briefly flashed at a random position on the screen. The position of both eyes was recorded by a video-based recording device (200 Hz), head position was recorded by active infrared marker tracking (200 Hz) and gaze orientation was reconstructed [5].

We analyzed how the orienting gaze shift towards the flash was programmed and how these saccades compensated for the smooth gaze displacement [SGD] during the latency period. Multiple regression analysis showed that gaze saccades were programmed using position error at flash time [PE] and an estimation of SGD. Both the smooth eye (90%) and head displacement (75%) were used in programming the saccade.

In conclusion, we propose that the gaze control system uses a similar mechanism to program head restrained and head unrestrained saccades. Eye and head displacements during the saccade latency period were integrated to compensate for intervening eye and head movements.

Keywords— **gaze shift, eye-head coordination, remembered target, 2D pursuit, gaze saccade**

I. INTRODUCTION

A combined eye-head gaze movement is generally used to reorient the visual axis to a new center of interest. Compared to eye-only saccades, the accuracy of combined eye-head saccades remains accurate although the control of the two systems together is more complex. This complexity further increases when saccades and smooth pursuit tracking eye movements interact in a head-unrestrained manner.

With the head restrained, it has been shown that there is an interaction between the saccadic and the pursuit system [1] to ensure accuracy for reorienting movements executed during an ongoing movement. When programming a saccade during ongoing smooth pursuit, [1] has shown that the saccade amplitude is adapted to take the smooth target motion on the retina into account. Retinal target velocity is sampled by the brain and extrapolated in a predictive way so as to overcome the anticipated smooth eye displacement during the latency period of the saccade. However, when the target is briefly flashed, it is not possible to evaluate the eye velocity with respect to the target. Therefore, the brain must rely on extraretinal signals and integrate the velocity commands sent to the extraocular muscles in order to estimate the smooth eye displacement during the latency period [2,3,4] and to ensure accuracy of orientation.

Here, the question arises whether such a compensatory mechanism also exists during head-unrestrained tracking. Of particular interest is to know whether or not the addition of head displacements during the latency period is also taken into account in programming the saccade. We tested this for head-unrestrained gaze saccades towards targets flashed during ongoing head-unrestrained smooth pursuit.

II. MATERIALS AND METHODS

Eight healthy human subjects (4 men, 4 women, 22-32 years old) participated in this study after giving informed consent. All procedures were approved by the Université catholique de Louvain ethics committee.

A. Experimental setup

Subjects sat in darkness in front of a 1-m distant translucent tangent screen, which spanned about ±40° of their horizontal and vertical visual field. Their head was totally free to move. Two targets, a red and a green laser spot (each measured 0.5°), were back-projected to the screen via mirror galvanometers (GSI Lumonics, Billerica, LA). The position of the mirrors was controlled by a PXI system running LabView (National Instruments, Austin, Texas). The target position was sampled at 1 kHz. Two-dimensional (horizontal and vertical) eye movements were measured (200Hz) using a Chronos head-mounted video

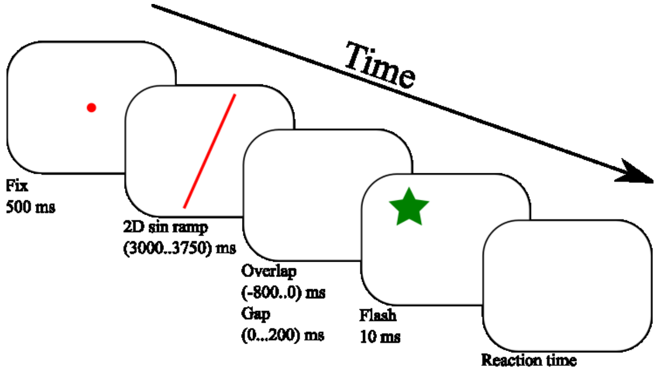

Fig. 1. Trial timing representation. A trial started with a fixation at the center of the screen for 500ms. Afterwards a pursuit target along a ramp is presented for a random time between (3000…3750) ms then a green target is flashed during 10 ms. During a reaction time period, subjects were asked to orient gaze to the memorized position of the flash. The protocol finished with a second red target fixation at the center of the screen for 500 ms.

eye-tracker (Chronos Vision GmbH, Berlin, Germany). To prevent from slippage of the helmet, a bite bar was mounted onto the helmet frame. Head position was measured using an infrared limb tracking system (Codamotion system, Charnwood Dynamics, Leicestershire, United Kingdom) which measured (200Hz) the position of a set of six infrared light-emitting diodes (IREDs) fixed to the Chronos helmet.

B. Protocol

Recording sessions were composed of blocks of 25 trials. Each trial started with a fixation of the red target at the center of the screen for 500ms. Next, the red target started to move along a randomly oriented ramp with a sinusoidal velocity, a random amplitude (between [20^o…25^o]) and a random frequency (between [0.6…1. 2] Hz) during a random time (duration: [3000…3750] ms).

Three conditions were studied with regards to the appearance of a green flashed target (duration: 10ms):

- *The gap condition:* The green target was flashed after the red pursuit target was extinguished. The gap duration was randomly selected in [200, 175, 150, 125, 100, 75, 50, 25] ms.
- *The no-gap no-overlap condition (NGNO):* The green target was flashed at the same time as the red pursuit target was extinguished.
- *The overlap condition:* The green target was flashed before the red pursuit target was extinguished. The overlap duration could randomly last for [100, 200, 300, 400, 500, 600, 700, 800] ms.

The probability of occurrence of one of the three conditions was equally distributed. After the flash presentation, an orientation period was allowed and subjects were requested to orient gaze to the memorized flash position. The total duration of a trial was 6s; subjects knew that the trial was finished when a second red fixation spot was shown for 500ms at the center of the screen

C. Data analysis

The recorded data were stored on the hard disk of a PC for off-line analysis. Matlab® (The Mathworks, Natick, Massachusetts) was used to implement the analysis. Position signals (head position and eye orientation) were low-pass filtered by a zero-phase digital filter (cut-off frequency: 50 Hz). Velocity and acceleration signals were computed using a central difference algorithm.

The gaze corresponds to the position of the eye with respect to an inertial reference frame. We reconstructed the gaze orientation from the eye and head position and orientation measurements using a previously described procedure [5].

D. Data representation

The initial data were 3D data for the head and 2D data for the eye. For the analysis, we computed the intersection of the eye, head and gaze vectors with the plane of the targets.

Data were normalized with respect to the pursuit target direction either at flash time for NGNO and overlap conditions or at the target disappearance for gap condition. The movement was decomposed into two components: the direction parallel to pursuit (X axis on figures 2 and 3) and the direction normal to pursuit (Y axis on figures 2 and 3).

Saccades were detected using a Kalman filter on the eye-in-head orientation signal similar to [6] combined with a generalized likelihood ratio (GLR) algorithm [7]. Once a saccade was detected, its onset and its offset were computed with a traditional acceleration threshold ($750°/s^2$) on the eye-in-head signal. Every trial was visually inspected; if a saccade was not detected, we adjusted the acceleration threshold to $500°/s^2$.

We removed trials if a gaze saccade occurred in an interval of [-50…50] ms around the flash appearance or if the direction of the first gaze saccade was incoherent with the position of the flashed target. Those criterions removed cases in which the localization of the flash was erroneous. We also removed trials with a final error bigger than 16°. We finally removed trials where the first saccade after the flash was directed towards the pursuit target and not towards the flash position (catch-up saccade).

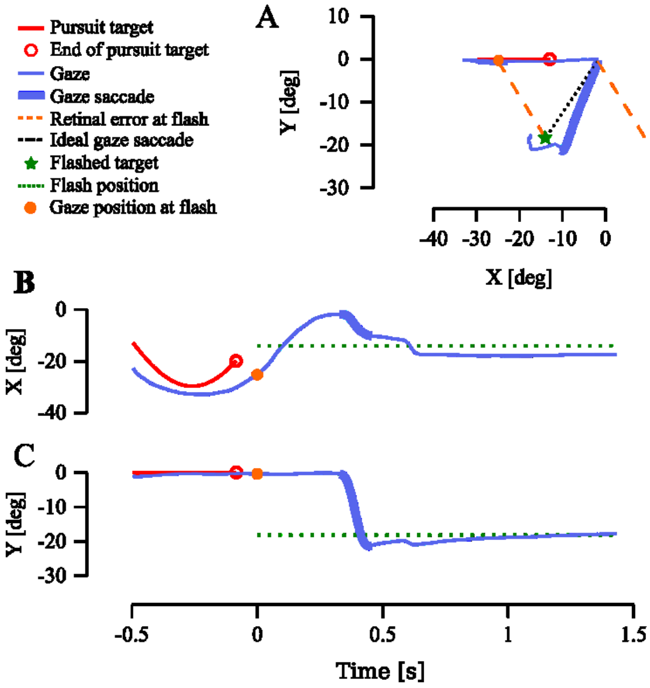

Fig. 2. Long latency trial. A: spatial representation of gaze (blue line), pursuit target (red line) and flashed target (green star). B: displacement parallel to pursuit of gaze and targets as a function of time (same colors conventions as panel A). C: displacement parallel to pursuit of gaze and targets as a function of time (same color convention as panel A).

III. RESULTS

We collected a total of 6533 trials out of which 2815 were valid trials (~43%). In valid trials 1146 were gap trials (~41%), 912 were No Gap No Overlap (NGNO) trials (~32%) and 746 were overlap trials (~27%).

A. Typical trials

Figure 2 shows a typical long latency trial (latency: 335ms) in gap condition (gap duration: 50ms). Panel A shows the spatial representation of gaze and targets; panel B-C represents respectively position along the direction parallel to pursuit of gaze and targets and position along the direction normal to pursuit of gaze and targets, both in function of time. When the second target was flashed, the gaze was located at the orange disk. One can see that between flash presentation and saccade execution, the gaze has moved mainly along the direction parallel to pursuit (displacement along X: 17.5°). The only visual information that the subject had in order to make his orientating movement was the retinal error at flash time (represented by the left orange dashed line). However, the saccade movement was better correlated with the ideal gaze saccade (black dashed line) than with the retinal error information (right orange dashed line).

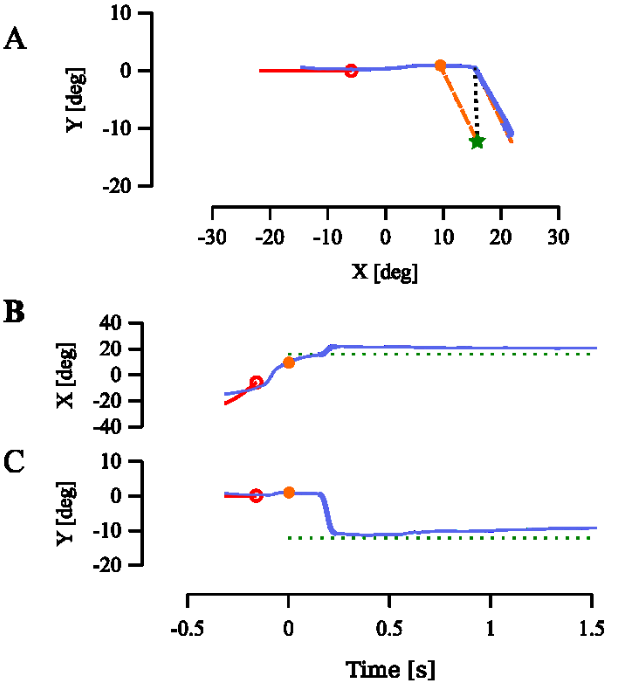

Fig. 3. Short latency trial. Same conventions as figure 2. A: spatial representation, B: displacement parallel to pursuit as a function of time, C: displacement normal to pursuit as a function of time.

Figure 3A-C shows a typical short latency trial (latency: 150ms) in gap condition (gap duration: 100ms). The same representation as Figure 2 is used. Here the gaze displacement along the direction parallel to pursuit (5.7°) is smaller than the one on figure 2. One can see that now the gaze saccade was better correlated with the retinal error at flash time.

A visual comparison of trials on figures 2 and 3 shows that for different latencies the behavior of the orienting gaze saccade is different.

B. Compensation index

To quantify the influence of the latency on the accuracy of the orientation process, we computed a compensation index. First, we defined PE_{end} as the error along the direction parallel to pursuit with respect to the flash position at the offset of the first saccade and SGD as the Smooth Gaze Displacement (displacement without any saccade) along the direction parallel to pursuit between the flash presentation and saccade onset. The compensation index (CI) is defined as:

$$CI = \left(1 - \frac{PE_{end}}{SGD}\right) * 100 \qquad [1]$$

A compensation index of 100% means that the displacement during the latency period is perfectly integrated by the brain and that the final error equals zero. A 0% compensation index means that there was no integration of the smooth gaze displacement that occurred during the latency period and that the final error is equal to the SGD.

One can compute the compensation index for the trials of figures 2 and 3. Values were 86% and -11% respectively.

The analysis of CI evolution in function of the latency revealed that the longer the latency, the bigger the CI.

C. Regression analysis

A regression analysis showed that gaze saccade amplitude is well correlated with position error at flash time (PE_{flash}) for short latency saccades. For long latency saccade, a multiple regression analysis showed that gaze saccade amplitude is better correlated with a multiple regression model integrating PE_{flash} and the SGD that occurred during the latency period than by a simpler model with only PE_{flash}. Regression analysis on eye and head showed that 90% of the eye displacement and 75% of the head displacement that occurred during the latency period were taken into account to program the saccade.

IV. CONCLUSIONS

We provide evidence for a similar mechanisms to keep track of smooth eye and head movement in darkness. Two main strategies were possible to execute an orienting movement. Either the gaze saccade was realized as fast as possible (and only used the information from PE_{flash}) to minimize the effect of the smooth gaze displacement during the latency period, or the system takes some time to integrate extraretinal eye velocity signals which allowed for (at least partial) compensation of smooth gaze displacement.

The computation of the compensation index showed that the latency has a direct effect on the compensation. We showed that the longer the latency, the bigger the compensation. The regression analysis confirmed that the brain needs some time to integrate the gaze displacement that occurred during the latency and therefore to correct saccade amplitude. Saccade amplitude was programmed using the retinal error at the moment of the flash and an estimation of both eye and head displacements if available.

We therefore suggest that the gaze control system uses similar mechanisms to program head restrained and head unrestrained saccades towards memorized targets and that the head movement during the latency period is well integrated into the compensatory mechanism.

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author:

- Author: Pierre Daye
- Institute: CESAME/UCL
- Street: Avenue Georges Lemaitre, 4
- City: Louvain-la-Neuve
- Country: Belgium
- Email: pierre.daye@uclouvain.be