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Quantitative Analysis of Catch-up Saccades Executed during Two-dimensional Smooth Pursuit

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Introduction

Smooth pursuit eye movements are normally made when we track an object moving smoothly in the visual environment. The role of the smooth pursuit system is subsequently to match the eye velocity to the target velocity and to keep the image of the object near the fovea, the highest acuity zone in the retina. When target velocity is too large, errors during pursuit are eliminated by saccadic eye movements which in this case are called catch-up saccades. It is necessary to point out that smooth pursuit eye movements are controlled by visual feedback contrary to catch-up saccades, which are executed without visual feedback. The mechanisms that govern the decision to switch from smooth pursuit eye movements to catch-up saccades, which have very different dynamics, are still poorly understood.

Saccades are fast, dart-like, conjugate eye movements (maximum velocity 500 deg/s) used to position the fovea of the eyes in a time optimal manner. The sensory information, which the saccadic system uses, is the difference between the target and eyesight positions, i.e., position error. Their control is based on an efference copy of the commands of the oculomotor system. Contrary, smooth pursuit eye movements are much slower than saccades (eye velocity usually is smaller than 50 deg/s) and are controlled by visual feedback. During smooth pursuit, the oculomotor system cannot rely only on the position error to orient toward moving target. The sensory information is the relative motion of the target with respect to the fovea, or retinal slip.

The goal of this study is to understand the sensory conditions leading to the occurrence of catch-up saccades during smooth pursuit.

Describing the task

The neural subsystem generating the rapid, saccadic eye movements used to capture new object, is quite distinct from that performing the pursuit, tracking movements. For the refixation saccades to stationary targets, the sensory signal is the position error between target projection in the periphery of the retina and the fovea. Saccadic latency, or reaction time, typically refers to the time from the onset of the non-predictable step of target jump to the onset of the saccadic eye movement initiated to foveate the displaced target. It is approximately 180 to 200 msec, with standard deviation of 30msec [1]. The relationship between the peak velocity and the amplitude of the saccade, called the main sequence, typically separate these movements from the limb or head coordinated movements. Main sequence illustrate that peak velocity is 410 deg/sec for 10 deg amplitude of the saccade, 500 deg/sec for 15 deg amplitude and 650 deg/sec for 20 deg amplitude [1]. When the target is moving and the target and eye velocities are different, retinal slip take place. To overcome these slip and delay in the neural pathways the oculomotor system uses prediction of future target motion to program catch-up saccades to moving target.

Previous studies used artificially produced one-dimensional short duration time-continuous trajectories with target jump or changes of the target velocity included to trigger catch-up saccades [2, 3,]. Due to short duration, these experiments did not clearly distinguish the influence of the integrated target velocity. The batches of catch-up saccades, which were dominating in our experiments, were never analyzed in the published literature (exception [4]). This research let us more clearly understand the programming of catch-up saccades during sustained pursuit.

In this research we investigated quantitative parameters of catch-up saccades such as: main sequence (relationship between the peak velocity and the amplitude of catch-up saccades), intersaccadic interval in the batch of catch-up saccades, the relationship between the transient and integral target velocities and the peak velocity of catch-up saccades. We proposed model, which explains the role of the position error and retinal slip and the target velocity in the triggering of the bunch catch-up saccades.

Method

Movements of both eyes were recorded with eye tracker *EyeGaze System* produced by LC Technologies

Ltd. Among the five subjects, two authors participated in the experiments. Two-dimensional target trajectories were presented on the computer screen. Subjects were asked to track the target (white spot) moving with a non-predictable time-continuous trajectory. Two-dimensional identical target trajectories performed with low (L), medium (M) and high (H) velocities were used in all trials. The peak velocities of the target movements were 12.5, 25 and 50 deg/s and durations of the trials - 66, 33 and 16s, respectively. The trajectories as well as velocities of the target and tracking eye movements were recorded and analyzed. Quantitative parameters of catch-up saccades, such as the amplitudes *A*, the peak velocities E_P, and the intersaccadic intervals T_I in the batch of catch-up saccades were computed. The position errors P_E and retinal slips R_S at the onset of catch-up saccades also were checked.

Experimental results

In the Fig. 1 a segment of the target and tracking eye movement trajectories are shown. The duration of the segment is 4 seconds and the peak velocity is 24deg/sec. Time interval between two diamonds in the eyesight trajectory is 16.6 msec. The larger intervals between two diamonds (larger eye velocities) let us to find catch-up saccades, which are marked by numbers from 1 to 10.

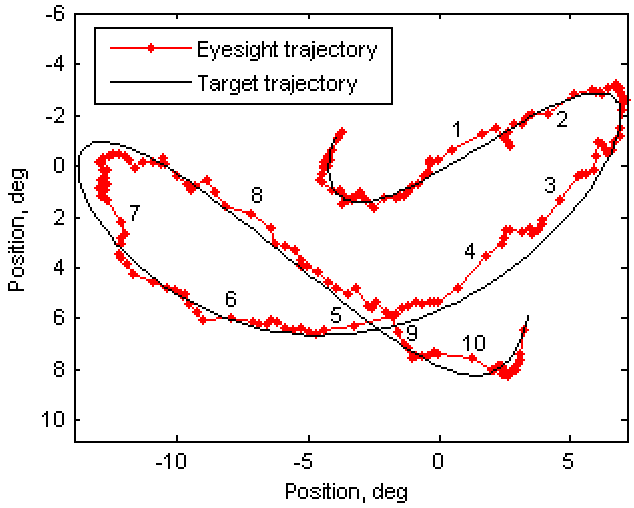

Fig. 1. A segment of the target and tracking eye movement two-dimensional trajectories. Catch-up saccades are marked by the numbers from 1 to 10. The same numbers of the same catch-up saccades are used in the Fig. 2

In the Fig. 2 the same segment as in the Fig. 1 of the target and tracking eye movement trajectories (A), position error (B) and eye velocity (C) in the horizontal direction as a function of the time are plotted. In this figure (plot C) 10 catch-up saccades, shaped as bell-wave jerk, could be clearly observed.

Furthermore, in the Fig. 2 we can see other parameters, which take place in the catch-up saccades programming: the position error (trace B), the retinal slip R_S, the time interval T_I between two catch-up saccades in the batch of them, the amplitude *A* and the peak velocity E_P of catch-up saccades. Each time, when the catch-up saccade is elicited, the position error P_E is reduced by the amount of catch-up saccade amplitude *A*.

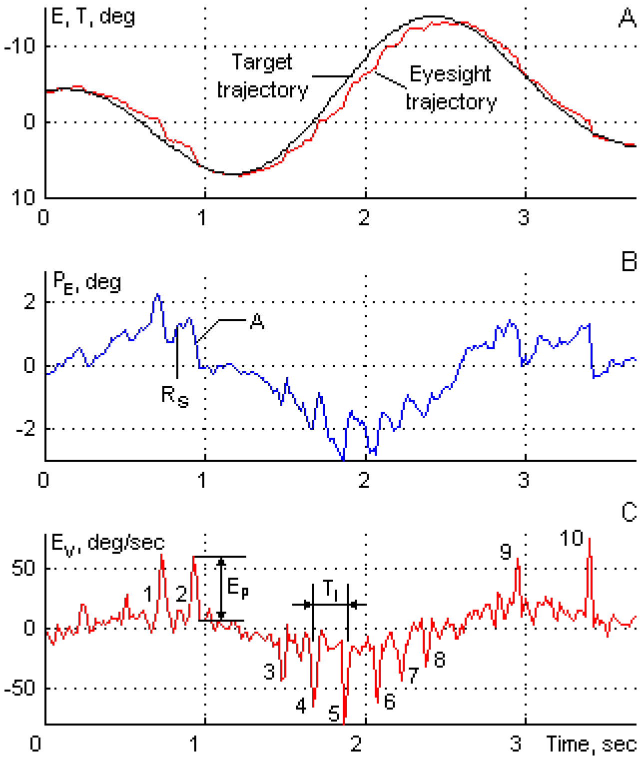

Fig. 2. A segment of the target *T* and tracking eye movement *E* trajectories (A), position error (B) and eye movement velocity (C) in the horizontal direction as a function of the time

To explain how the transient and integral target velocities (T_V, T_{VI}) influence the parameters of catch-up saccades and the parameters which trigger catch-up saccades, time-continuous trajectories were repeated with 3 different target velocities L, M and H. Computed experimental results are illustrated in the Fig. 3, 4, 5, 6.

In the Fig. 3, the retinal error R_E and retinal slip R_S as a function of the transient target velocity T_V for 3 integral target velocities: low (L), medium (M) and high (H) are shown.

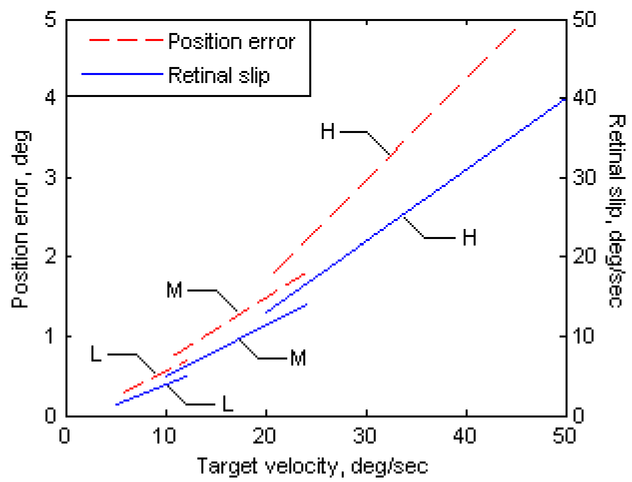

Fig. 3. Position error P_E, and retinal slip R_S as a function of the transient target velocity for 3 integral target velocities L, M and H

There we can see that the retinal errors and retinal slips linearilly increase when the transient target velocity increases and this linearity is not strongly influenced by the different integral target velocities T_{VI}, marked in the figure by letters L, M and H.

The most interesting finding in the present study was that the peak velocities of catch-up saccades E_P did not depend on the integral target velocity T_{VI}, and depend only on the transient target velocity T_V. This relation is presented in the Fig. 4.

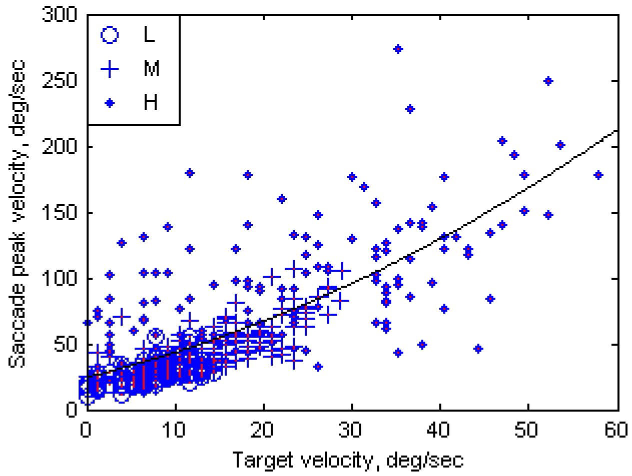

Fig. 4. Relationship between peak velocity of catch-up saccades E_P and transient target velocity T_V for 3 integral target velocities

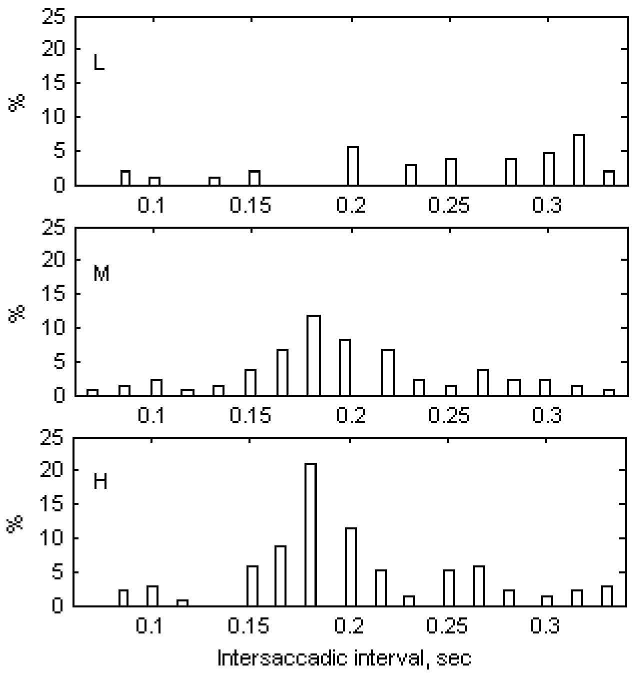

Fig. 5. The distributions of the intersaccadic time intervals T_I between two catch-up saccades in the batch of them for 3 integral target velocities L, M and H

The distributions of the intersaccadic time intervals T_I between two catch-up saccades in the batch of them for 3 integral target velocities are presented in the Fig. 5. There we can see that the most regular time intervals in the range of 0.15 – 0.2 sec are seen for higher integral target velocities. Contrary to the low target velocity, when oculomotor system has time for decision, when to elicit catch-up saccade, during higher target velocities it is forced to perform it as quickly as possible.

In the Fig. 6 a segment of the target and eyesight velocity trajectories for two integral target velocities are presented. These examples let us to understand that for larger differences between the target and eye velocities (smaller gain) catch-up saccades are elicited more frequently and with larger peak velocities.

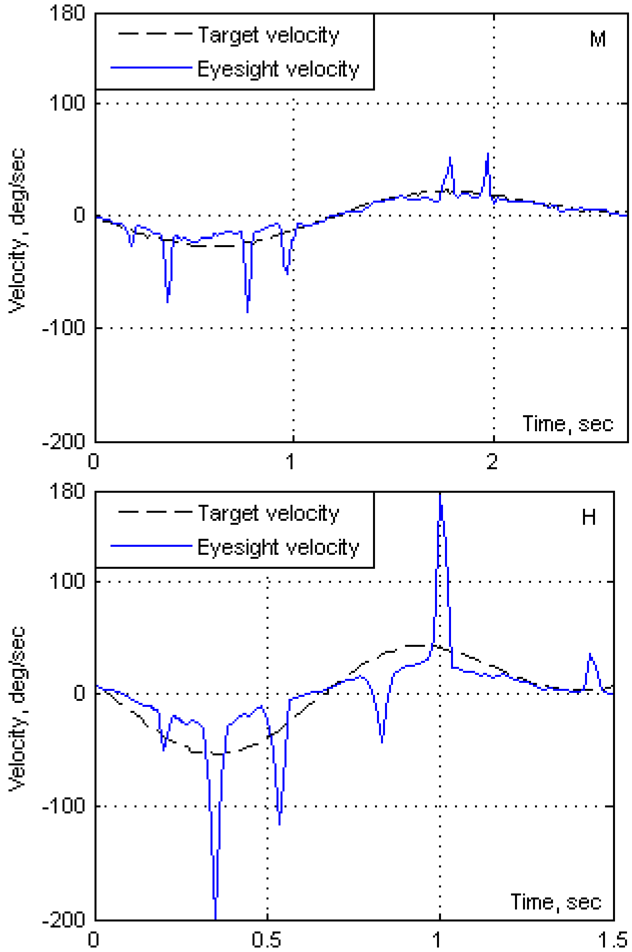

Fig. 6. A segment of the target and eyesight velocity trajectories for two integral target velocities: M (upper) and H (lower)

Discussion

Catch-up saccades correct for the position error that accumulates during smooth pursuit tracking when the gain of the pursuit (ratio of the eye and target velocities) is less than 1.0. Due to small gain, the more the target velocity increases, the more the position error increases [1], therefore larger correction by catch-up saccades must be made. Assuming that during pursuit, the eyesight should not lose the target, it has to come the same way (distance D_E) as the target D_T. Therefore, for the time interval between t_1 and t_2 we can define that

$$D_T = \int_{t_1}^{t_2} T_V(t)dt = kD_E = k\int_{t_1}^{t_2} E_V(t)dt\ . \qquad (1)$$

In this equation, $T_V(t)$ and $E_V(t)$ are the target and eye velocities, and k represent coefficient evaluating shorter distance for the eyesight way when the trajectory of the target is predictable.

Equation 1 represents general idea of our research and explains what programming strategy oculomotor system uses eliciting batches of the catch-up saccade inclusions during smooth pursuit. First of all, we have to have in mind that the shortest time interval between two catch-up saccades in the batch of them is 150ms. Because of the suppression of vision during saccades, this time interval between two catch-up saccades is necessary for the vision to get new information about the real target position and to anticipate the direction of the next catch-up saccade. Second rule is that for a given gain of less than 1.0, oculomotor system prefers to make many corrective catch-up saccades with small amplitude instead of a few large. Small amplitude catch-up saccades have a shorter duration and overcome smaller distance, therefore there are less dangerous for vision to lose the target. For the larger target velocities due to a shortage of the time, the oculomotor system instead if making many small catch-up saccades is forced to make only one or a few large amplitude catch-up saccades as seen in the figure 6. To compensate position error and retinal slip, which appears due to a difference of the target and eye velocities, catch-up saccades with larger peak velocity and amplitude are needed. The model of this assumption during the time interval from t_1 to t_2 (between two catch-up saccades) is

$$\int_{t_1}^{t_2} T_V(t)dt - \int_{t_1}^{t_2} E_V(t)dt = k\frac{3}{4}V_P D . \qquad (2)$$

Because of the clear relationship between the peak velocity V_P and duration D of catch-up saccades, equation 2 let us to find parameters of catch-up saccades according to the target and eye velocities. If the trajectory of the target movement is predictable and vision is sure that the target will be not lost, vision lets to the oculomotor system to make shorter way (coefficient k <1).

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The purpose of this research was to investigate quantitatively the catch-up saccades occurring during smooth pursuit. In our experiment, to evoke catch-up saccades we used two-dimensional non-predictable time-continuous target trajectories submitted with 3 peak velocities: 12.5, 25 and 50deg/s. From the experimental results we computed the relationships of the parameters of catch-up saccades: the amplitude, the peak velocity, the time interval between two-saccades in the bunch of them with the parameters such as the position error, the retinal slip and the transient and integral target velocities. On the basis of the analysis of these relationships, we proposed the model how catch-up saccades are programmed and how the slow (smooth pursuit) and the rapid (saccadic) eye movements interact. Ill. 6, bibl. 5 (in English; summaries in English, Russian and Lithuanian).

В. Лаурутис, Г. Даунис, Р. Земблис. Количественное исследование двухкоординатных схватывающих саккадических движений глаз, получаемых во врея плавных траекторий ее движения // Электроника и электротехника. – Каунас: Технология, 2010. – № 2(98). – С. 83–86.

Описывается количественное исследование схватывающих саккадических движения глаз, получаемых во время плавного движения цели. В нашем эксперименте схватывающие саккады были вызваны применив по непрогнозируемой, двухкоординатной траектории плавно движующуюсю цель со скоростью 12.5, 25 и 50 град/сек. На основе экспериментальных результатов были вычислены зависимости между параметрами схватывающих саккад: амплитудой, пиковой скорости, интервала времени между двумя саккадами в их пачке и таких параметров как ошибка положения цели на сетчатке, скорость скольжения цели на сетчатке, а также моментная и интегральная скорости цели. На основе анализа этих зависимостей была предложена модель, как програмируются схватывающие саккады и как медленные (плавные следящие) и быстрые (сакадические) взаимодействуют между собой. Ил. 6, библ. 5 (на английском языке, рефераты на английском, русском и литовском язю).

V. Laurutis, G. Daunys, R. Zemblys. Dviejų koordinačių pagaunančiųjų sakadų, atsirandančių tolydinės taikinio judesio trajektorijos metu, kiekybinė analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 2(98). – P. 83–86.

Aprašomos kiekybinės pagaunančiųjų sakadų, atsirandančių taikiniui judant tolydine trajektorija, charakteristikos. Eksperimento metu pagaunančiosios sakados buvo gautos panaudojus tolydinę nežinomu dėsningumu judančio taikinio trajektoriją, kurios pikinis greitis buvo 12, 25 ir 50 laipsn/s. Iš gautų eksperimentinių rezultatų buvo nustatytos priklausomybės tarp pagaunančiųjų sakadų parametrų: amplitudės, pikinio greičio bei laiko intervalo tarp dviejų gretimų sakadų jų pakete ir tokių parametrų kaip padėties (sekimo) paklaida akies tinklainėje, paklaidos greitis (slydimas akies tinklainėje) bei momentinis ir integralus taikinio greitis. Išanalizavus šias priklausomybes, pasiūlytas modelis, kaip pagaunančiosios sakados yra programuojamos ir kaip lėti (švelnaus sekimo) ir greiti (sakadiniai) akies judesiai sąveikauja tarpusavyje. Il. 6, bibl. 5 (anglų kalba, santrauka anglų, rusų ir lietuvių k.).