Quantitative Analysis of Two-Dimensional Catch-Up Saccades Executed to the Target Jumps in the Time-Continuous Trajectory

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Abstract— **The purpose of this research was to investigate quantitatively the catch-up saccades occurring during smooth pursuit. In the first experiment, to evoke catch-up saccades we used high velocity predictable two-dimensional time-continuous target trajectories. In the second experiment, catch-up saccades were evoked using target jump paradigm during sustained two-dimensional pursuit. Target jumps in the different directions were presented at the unexpected moments and positions of the interrupted time-continuous target trajectory. From the experimental results we made a comparison of the main sequences (relationship between peak velocity and amplitude) of the catch-up and refixation saccades and found that they are different. Also we can conclude that the peak velocity of catch-up saccades is strongly correlated with the velocity of the smooth pursuit target component. We found that both position error and retinal slip are taken into account in catch-up saccades programming to predict the future trajectory of the moving target. Ill. 5, bibl. 5 (in English, summaries in English, Russian and Lithuanian).**

Keywords— **Eye movements, Smoth pursuit, Sacadic eye movements, Catch-up saccades.**

I. Introduction

Eye movements exist to aid vision by directing gaze towards new objects of interest and, if those objects move, by tracking them. This serves to bring pertinent retinal images into the fovea – the region of the most acute vision. An interesting feature of the brain's control of eye movements is its modular organization, with different subsystems mediating special functions. The neural subsystem generating the rapid, saccadic eye movements used to capture new object, is quite distinct from that performing the pursuit, tracking movements (second subsystem). The third subsystem – vestibular ocular reflex (VOR) is entirely concerned with generating eye movements that compensate for rotations of head and so tends to stabilize the eyes with respect to the environment. To achieve single vision by two eyes they must be aligned on the target. This has resulted in the evolution of a fourth subsystem to generate vergence eye movements. The nervous system controls all of these eye movements with considerable precision and ability to adapt its performance trough motor learning processes [1].

Recently all four eye movement subsystems are properly studied and many characteristics and parameters of them are well known. More interesting topics of the investigation now are how these subsystems collaborate together or subsequently take in action one after another [2]. This research is dedicated to reveal interaction between saccadic and smooth pursuit eye movements when target tracking is interrupted by catch-up saccades.

Saccades are fast, dart-like, conjugate eye movements used to position the fovea of the eyes in a time optimal manner. They could be categorized into refixation saccades and microsaccades, which are seen only during fixation. Normometric saccadic refixations could be either single-step or multi-step movements. Multi-step (usually double-step) saccades are executed in two-steps: primary and corrective saccades. Primary saccade could be too small (hypometric) and too large (hypermetric) with respect to the intended target position. Only 30 % of saccades are single-step and precisely reaches new target. From the rest of the multi-step saccades only 30 % are hypermetric. Normometric saccades demonstrate pretty common trajectories. Saccadic latency, or reaction time, typically refers to the time from onset of the non-predictable step of target movement to onset of the saccadic eye movement initiated to foveate the displaced target. It is approximately 180 to 200 msec, with standard deviation 30 msec. Relationship between peak velocity and amplitude of the saccade, called the main sequence, typically separate these movements from other limb or head 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.

Catch-up saccades are seen in the eye tracking trajectory of the smoothly moving target, when target velocity becomes too large for smooth pursuit eye movements. Also catch-up saccades could be executed to the target jumps in the time-continuous trajectory. In this case, at some moments smooth pursuit eye movements are interrupted by quick eye jumps – catch-up saccades, which allow maintain the target on the fovea. Parameters of the catch-up saccades differ from refixation saccades and they are investigated only in one dimensional mode [3].

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II. Aim and tasks of the work

In this research we investigated quantitative parameters of catch-up saccades such as: main sequence (relationship between peak velocity E_p and amplitude A of catch-up saccades), saccadic latency T_d, and the precision of the extrapolation of the target trajectory by smooth pursuit eye movements during time interval T_e between target jump and catch-up saccade onset and time interval T_r when after catch-up saccade smooth pursuit behavior is restored.

Further investigation was focused on the finding relationship between the quantitative parameters of the catch-up saccades and the velocity of the time-continuous target trajectory.

For refixation saccades to stationary targets a sensory signal is the position error between target projection in the periphery of the retina and the fovea. When the target is moving and the eye and target velocities are different, retinal slip took place. To overcome these slip and delay the oculomotor system uses prediction of future target motion to program catch-up saccades to moving target. Previous studies did not clearly distinguish the influence of target velocity, position error, retinal slip and prediction in catch-up saccades programming [4].

III. Method

Movements of both eyes were recorded with eye tracker *EyeGaze System* produced by LC Technologies Ltd. Healthy subjects without any known oculomotor abnormalities were recruited after informed consent. Among the five subjects, two authors participated in the experiments. Two-dimensional target trajectories were presented on the computer screen. During first experiment, subjects were asked to track target (white spot) moving in the clock-wise direction. Square-shape and circle-shape target trajectories with angular velocities in the range of 10 - 50 deg/sec were used. Two-dimensional positions, amplitudes and velocities of the catch-up saccades were recorded.

In the second experiment, subjects were asked to track target moving with non-predictable time-continuous trajectory. At the randomly chosen time, time-continuous trajectory was interrupted by target jumps, amplitudes and directions of which also was random. Trajectories of catch-up saccades executed as the reactions to the target jumps were analyzed. Quantitative parameters of the catch-up saccades, such as reaction time (saccadic latency T_d), amplitudes A, peak velocities V_p, were measured. Also the extrapolation ability during time interval between target jump and catch-up saccade onset was evaluated.

IV. Experimental results

Four typical examples of the onset positions of catch-up saccades obtained during tracking of the targets which were moving in the clock-wise direction by square-shape and circle-shape trajectories are shown in Fig. 1. There we can see that for 10 times repeated trials catch-up saccades were more concentrated on the corners of the squares.

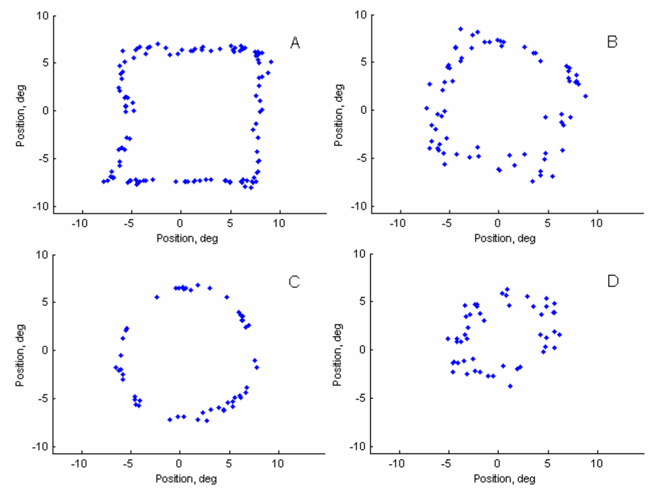

Fig. 1 Two-dimensional positions of catch-up saccades obtained during tracking of the square-shape (A, B) and circle-shape (C, D) target trajectories. Velocities of the target trajectories were 20 deg/sec for (A, C) and 50deg/sec for (B, D)

At these points the target trajectories change the movement direction from horizontal to vertical. Therefore, the control system of the smooth pursuit eye movements also is forced to change tracking direction. Pier of the horizontal eye globe muscles have to stop horizontal movement and vertical muscles start to act. This elicits tracking errors which are eliminated by catch-up saccades.

Two-dimensional positions of the catch-up saccades in the figure 1 (C, D) obtained during tracking of circle-shape target trajectories more clearly demonstrates that even when eyesight moves in the circle catch-up saccades occurs when target changes movement direction from vertical to horizontal and from horizontal to vertical.

In the figure 1 C, D, when target velocities were increased to the 50 deg/sec, the shape of eyesight trajectories differs from the target trajectories. They have angular shift in the clock-wise direction what demonstrates anticipation (focused on the future target position) of the predictable target trajectory.

Investigation of the relationship between the peak velocities of catch-up saccades and the target velocities during pursuit of the predictable target trajectories reveals close correlation between them (Table 1).

Table 1 Relationship between target velocity Vt and catch-up saccade peak velocity Vp in deg/sec

V_t	10	20	30	40	50
V_p	43	66	95.5	128	164.5

In the figure 2, the trajectories of catch-up saccades in the horizontal x and vertical y directions as reaction to the target jump executed during time-continuous movement are shown.

Oculomotor system demonstrates common (reflexive) behavior during ten trials elicited to the same target jump in the non-predictable target trajectory.

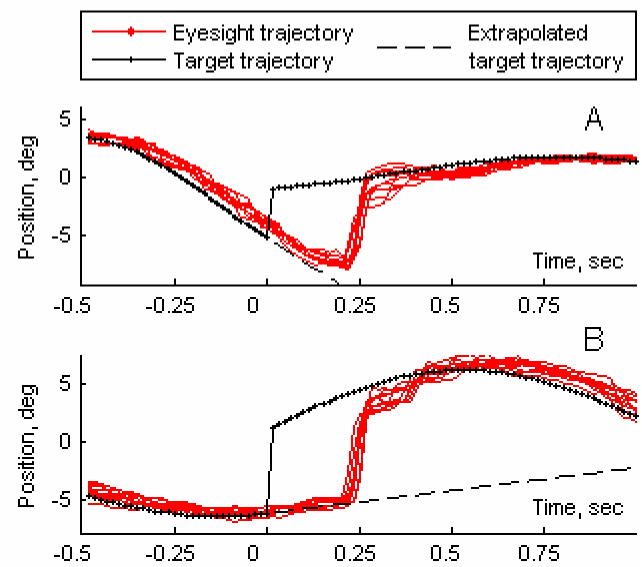

Fig. 2 Ten trajectories of catch-up saccades plotted together in the horizontal (A) and vertical (B) directions

Target and eyesight trajectories in the figures 3 and 4 could be divided in the few stages. From point 1 to point 2 we can see precise pursuit of the initial target trajectory. Target trajectory from point 2 to point 3 makes jump. Eyesight in this situation from point 2 to point 5 continues to extrapolate initial target trajectory what is more clearly seen in figure 4. From point 5 to point 6 eyesight jumps to the new position on the further time-continuous target trajectory. At the points 7 and 8 eyesight makes corrective saccades.

Most interesting finding in this research is notice that during catch-up saccade eyesight does not respond to the target jump, but catch future position in the time-continuous target trajectory (point 6). It means that vision is active during saccadic latency (points 2, 5).

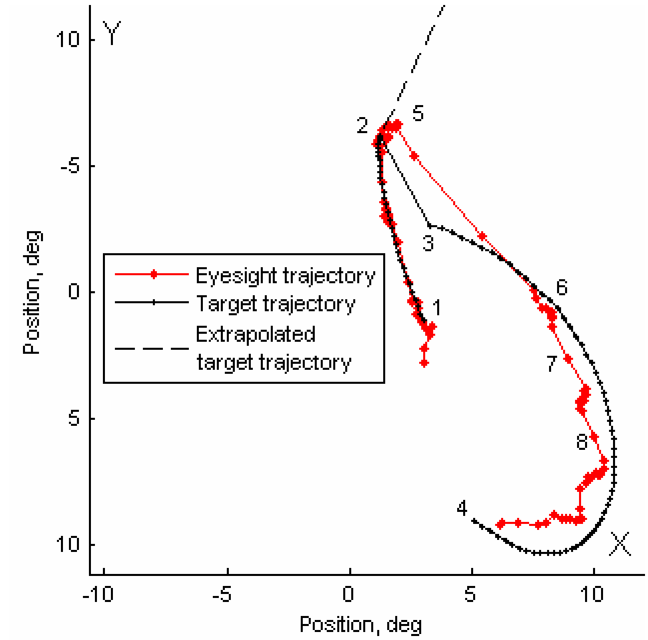

Fig. 3 Target trajectory (points 1, 2, 3, 6, 4) and eyesight trajectory (1, 2, 5, 6, 7, 8) obtained during two-dimensional tracking and plotted together

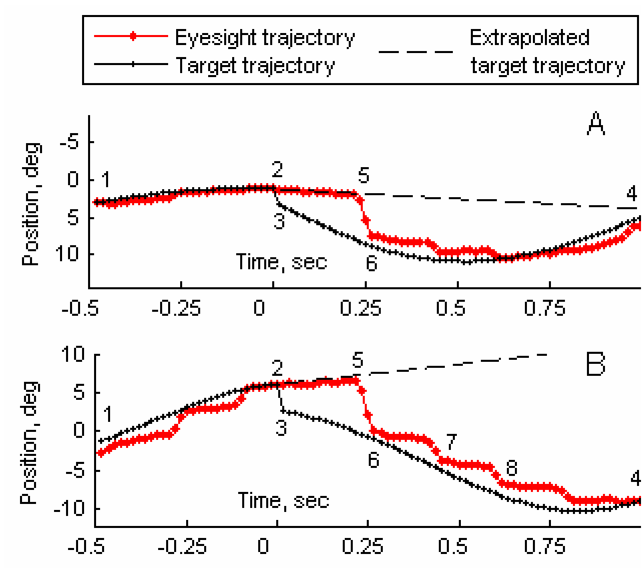

Fig. 4 The same target and eyesight trajectories as in the figure 3 plotted in the horizontal (A) and vertical (B) directions

Fig. 5 illustrates that the main sequences of the refixation and catch-up saccades differ. It means that the refixation and catch-up saccades are controlled by different neural circuits.

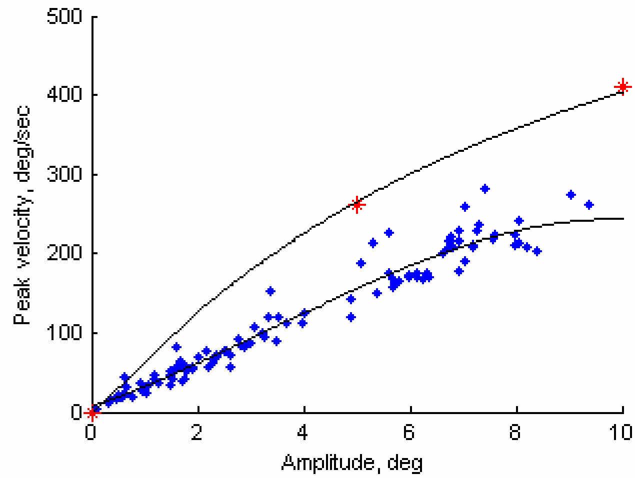

Fig. 5 Main sequences of the refixation catch-up and saccades

In the table 2, the parameters of catch-up saccades are placed. There we can see that saccadic latency T is stable for all five subjects. The extrapolation of the former target trajectory E was evaluated as the angular displacement between the real eyesight and extrapolated target trajectories at the end of the saccadic latency (point 5 in the figure 4)).

Table 2 Parameters of catch-up saccades

Subject	RZ	VL	GD	NR	AP
T, sec	0.25	0.28	0.24	0.22	0.26
E, deg	2.16	2.58	2.27	2.18	2.32

V. Conclusions

1. Catch up saccades aids the oculomotor system to reduce tracking error. Main parameters which induce catch-up saccades are position errors between the target projection on the retina and fovea and the retinal slip.

2. During two-dimensional tracking, when target changes the movement direction and therefore tracking errors increases, appearance of catch-up saccades is seen more often.

3. Saccadic latency for catch-up saccades (T_r = 240 msec) is bigger than for refixation saccades (T = 200 msec) and did not depend on the target velocity.

4. Peak velocity of catch-up saccades is strongly correlated with velocity of the smooth pursuit target component.

5. The relationship between the peak velocity and the amplitude (main sequence) for catch-up saccades differ from main sequence for refixation saccades.

6. Landing points of catch-up saccades do not depend on the amplitudes of the target jumps but is related with the new target position at the offset of catch-up saccade. The prediction of the future trajectory of the moving target requires more calculations and explains why the saccadic latency for catch-up saccades is bigger than for the refixation saccades.

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