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INFORMATIONAL CHARACTERISTICS OF THE DOUBLE-STEP SACCADIC EYE MOVEMENTS

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Abstract. Saccades have traditionally been studied in response to suddenly changing visual stimuli, such as jumping targets. The evaluation of saccadic eye movements based on the analysis of eye jump trajectories as reaction to the jumping targets is complicated. Time delays and errors of eye jumps are related to the target amplitudes and sequence presentation and must be determined in each type of the experiment.

In this research, information theory concepts are used to evaluate the control system of the saccadic eye movements which is defined as the information transfer channel. In this case, target jumping on the screen is defined as the input or the source information, the eyesight response trajectory on the screen – as the output information and the difference between them – as the lost information. The amount of information transferred over oculomotor channel is defined as the difference between the input and the lost information rates.

Majority of the saccadic eye movements are executed by two-step jumps: primary and corrective saccades. Therefore, the amount of information transferred over oculomotor channel has been measured separately after primary saccades and corrective saccades. We have found that the amount of information obtained during corrective saccades is two times larger than during primary saccades. Primary saccades with bigger amplitudes give more information despite a larger scatter of position errors at the end of jump for them.

Theoretical and experimental investigation let us formulate that channel information capacity of the saccadic oculomotor system is in the range of 14 - 15 bits/sec. This value was obtained when the intersaccadic interval was in the range of 0.4 – 0.5 sec.

Keywords: human oculomotor system**, s**accadic eye movements, information transfer, channel capacity.

1. Introduction

Saccadic eye movements serve to place the small center of the retina called the fovea on a different part of the visual field. The fovea is the part of the retina where visual receptor cells are most densely packed and objects projected on it are most sharply viewed. At the endpoint of saccade, the fixation information from the periphery of the retina is used to direct the various saccadic movements to the new objects of interest. Scanning of visual scenes, saccades and fixations are the most important eye movements used to acquire necessary information from the surrounding.

Trajectories and characteristics of the saccadic eye movements as biomedical engineering object are widely analyzed [1]. First, trajectories of saccades are close to optimal. The relationship between target amplitude and peak velocity, called the main sequence of saccades, is well known and identifies saccades among other types of limb movements. Several neural network models for saccade generation are proposed and fit experimental results of the recorded saccadic eye movements [2]. Instead of the first time proposed continuously sampled target position data for eye movement motor command, recently models have been based on sampled-data performance, which explains existence of 200 msec refractory time for the consequent saccade. Neural networks include not only visual guided commands but also the memory guided control (local feedback) performance of saccadic trajectories. Until quite recently, saccadic generator models involved ballistic or preprogrammed control to the desired eye position based on retinal position alone. Today, investigators are putting forth the idea that visual goal-directed saccades are controlled by a local feed-back loop that continuously drives the eye to the desired eye position [3]. A lot of research was dedicated to the precision of various types of saccades [4].

Precision of saccadic eye movements brings to the understanding that the oculomotor system actually performs two-dimensional measurement of the direction of the target. Large range of amplitudes (including head and trunk movements) big peak velocities (until 500 deg/sec) and short intersaccadic intervals (less than 1 sec) make the oculomotor system more attractive for fast angular measurements. Results obtained from the visuo-oculomotor system could be used for the visuo-motor control in a wide variety of the man-machine structures.

2. Situation overview

Figure 1 shows typical trajectories of the five refixation eye saccades made to the different target positions with intersaccadic interval equal 1 sec. Trajectories consist of the saccadic latencies of about 200 msec, first eye jumps (primary saccades) with large velocities, slow drifts, corrective saccades and fixational micromovements.

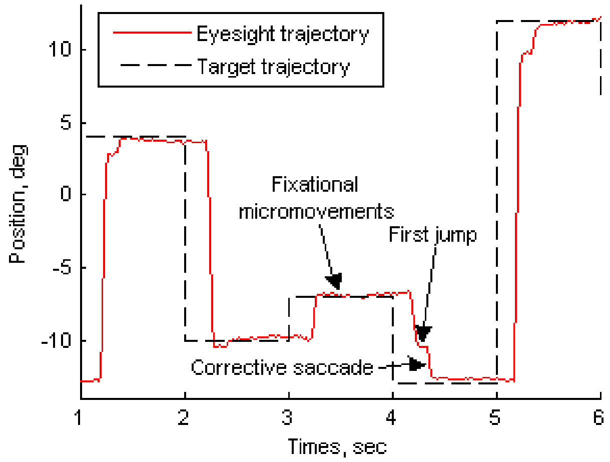

Figure 1. Trajectories of target position and saccadic eye movements made to the five target amplitudes with intersaccadic interval equal 1 sec.

Normal saccades can be either too small (hypometric) and undershoot the target or too large (hypermetric) and overshoot the intended target position. About 70% of primary saccades usually are hypometric [4]. They have the normal gain (that is, the amplitude of the initial eye movement divided by the amplitude of target jump) values 0.92 ± 0.03. Hypometric saccades represent a normal strategy adopted by the saccadic system so that any subsequent corrective saccade needs a computation of the amplitude only but not the direction. Hypermetric saccades, which occur in 13% of trials, initially overshoot the target and subsequent, visually guided corrective saccades, are elicited to attain foveation.

Jumping from one target to another, errors of saccadic eye movements could be evaluated in two-steps: error after first jump and final error, when saccade is completed. After first jump, error could be defined as the difference between a new target position and the point of eyesight before corrective saccade. Later the eye eliminates this error performing corrective saccade and minimizing it to the final error.

Saccades are more accurate when made between two simultaneously presented stationary targets than when the target periodically jumps between these same two spatial locations. When saccades were elicited to the targets, amplitudes and directions of which could not be predictable, the errors of the first step saccades were substantially bigger.

Fitts' law application for the evaluation of saccadic eye movements [5] was first attempt to define informational characteristic of the goal directed eye jumps. Fitts' law establishes the relationship between the difficulty of the movement task and the human performance in terms of movement time T:

$$T = a + b\log_2(\frac{2D}{W}) . \quad (1)$$

In this equation a and b are coefficients and depend on the type of movement. The task difficulty evaluated by the ratio of the distance to the target D and its size, is usually the width W. The task difficulty fits with the information rate obtained during a measurement $I = \log_2(2R/E)$, where R is the measurement range and E – the measurement error and could be defined in bits.

Model of the nature of the double-step saccades based on Bayesian decision theory [6] explains how the control system of the saccadic eye movements performs precise eye jumps. This behavior matches two-step Bayesian decision making process: first with large uncertainty and second, after getting additional information, more precise. Primary saccade, which is elicited in the conditions of the noisy visual estimation of the new target position and eye jump errors made by eye globe muscles, gets eyesight closer to the target. After primary saccade, visual estimation of the target position becomes more precise and second, small amplitude corrective saccade, gets eyesight on the target.

In this research, we propose a human control system of the two-step saccadic eye movements quantitatively evaluate as the informational transfer channel. In this case, we can define it by the amount of information transferred during the primary and corrective saccades separately.

3. Aim and tasks

Using information theory concepts, the control system of the saccadic eye movements could be defined as the informational transfer channel. In this case, a two-dimensional target position on the screen would be defined as the source or the input information of the oculomotor system, the eyesight position on the screen after complete eye jump as the output information and the difference between them as the lost information. If the frequency of the target jumps were increased, the source information rate also would be increased. Eye movements control system at the some threshold frequency of the target jumps would be no more capable to follow the target and the difference between target and eyesight positions or lost information would be quickly increased. This effect enables us to formulate the conclusion that human control system of the saccadic eye movements has the limit of the channel informational capacity. We propose to use this limit value as an important quantitative characteristic for evaluation of the control system of the saccadic eye movements.

The significant feature of the saccadic system is that a majority of eye movement trajectories are executed by two-step jumps. In this case, two separate steps obtain the information about the target direction. During the first step or the primary saccade, the eye jumps to the direction of the target and elicits saccade with the low accuracy. Speaking in informational terms, uncertainty of the direction of the target after primary saccade remains large.

Next step, which is called corrective saccade, will be performed after 150-200 msec delay put eyesight on the target, and reduce error to minimum. It enables eye to fixate the target. At the final point, the precision of the eyesight position on the screen is large and the uncertainty of the target direction is small, as it is caused only by the fixational eye movements.

Transformations of the uncertainties and probability distributions of the eyesight position errors during a two-step saccadic eye movement are shown in Figure 2. The probability distribution after the primary saccades (because of the dominating undershoot) fits the asymmetric Gaussian law and has a large standard deviation with mean value shifted to smaller amplitudes. The probability distribution after the second step during the target fixation fits the Gaussian law and has a small standard deviation and a mean value close to zero.

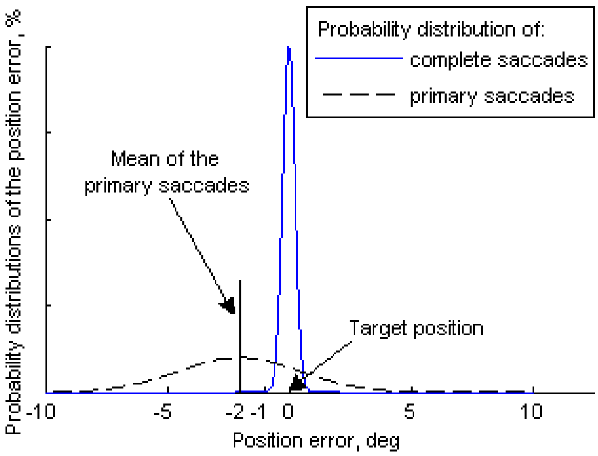

Figure 2. Probability distributions of position errors for primary and complete saccades

4. The Method

When the target jumps from one position to another, the saccadic eye movements control system is in action. In this case, we can assume that the input or the source information as well as two-steps response of the oculomotor channel are discrete.

If all target positions had equal probabilities and the probability distribution of the eyesight position errors fits the Gaussian law, the information rate transmitted over channel during one single primary saccade would be [7]:

$$I_{1S} = \log_2 \frac{k_x}{4.1\sigma_{1x}} + \log_2 \frac{k_y}{4.1\sigma_{1y}}. \qquad (2)$$

In this equation, k_x, k_y are the ranges of possible target amplitudes and σ_{1x} , σ_{1y} are standard deviations of the errors of the primary saccades in the horizontal and vertical directions, respectively.

The informational rate obtained only during the second step I_{2S} could be defined as the difference between information rates obtained during complete saccadic jump I_S and the first step jump I_{1S}.

$$I_{2S} = I_S - I_{1S} . \qquad (3)$$

Duration of the first step of the saccade depends on the amplitude of saccade and together with saccadic latency is about 0.25 sec. The next, corrective saccade, has approximately the same duration, therefore, after complete saccadic eye jump another target could be presented only after certain time limit, which is called intersaccadic interval *D*. In this research intersaccadic interval was changed from 0.25 sec to 3.0 sec. The channel information capacity as the largest amount of transferred information during saccadic eye movement session, when the duration of the experiment is long enough, could be obtained by the equation [6]:

$$C_S = \max_D [\frac{1}{D}(\log_2 \frac{k_x}{4.1\sigma_x} + \log_2 \frac{k_y}{4.1\sigma_y})]. \qquad (4)$$

The largest value of C_s (the channel capacity) could be obtained at the shortest intersaccadic interval *D*, (largest information rate at the input of the oculomotor channel) at which errors of saccadic eye movements remains small.

5. Results

Experimental data were obtained from five subjects and statistically operated. Eye movements in all experiments were recorded using LC Technologies Ltd produced eye tracker *EyeGaze System*. Targets were presented on the computer screen in 1-degree angular displacement between each another. The number of targets was k_x = 27 rows in the horizontal direction and k_y = 21 columns in the vertical. Target positions were presented in the random order with the intersaccadic interval *D*. During the experimental session, intersaccadic interval *D* was tuned as short as possible until eyesight responses to all switched on one after another targets had been correctly executed. We found that the shortest intersaccadic interval was *D* = 0.2 sec. Experiments were repeated at the intersaccadic intervals in the range of 0.2 – 3 sec. The accuracy of saccades was measured by defining the difference between target and eyesight positions separately for primary saccades and after complete saccades. Probability distributions of position errors of the primary saccades for 10 and 20 degrees of the target amplitudes are shown in Figure 3. Experimental results indicate that the scatter of error values of primary saccades is larger for the bigger target amplitudes. The mean values of the probability distributions m_{1x}, m_{1y} are also larger for the bigger target amplitudes and increase approximately from one deg for 10 deg saccade amplitudes to two deg for 20 deg saccade amplitudes.

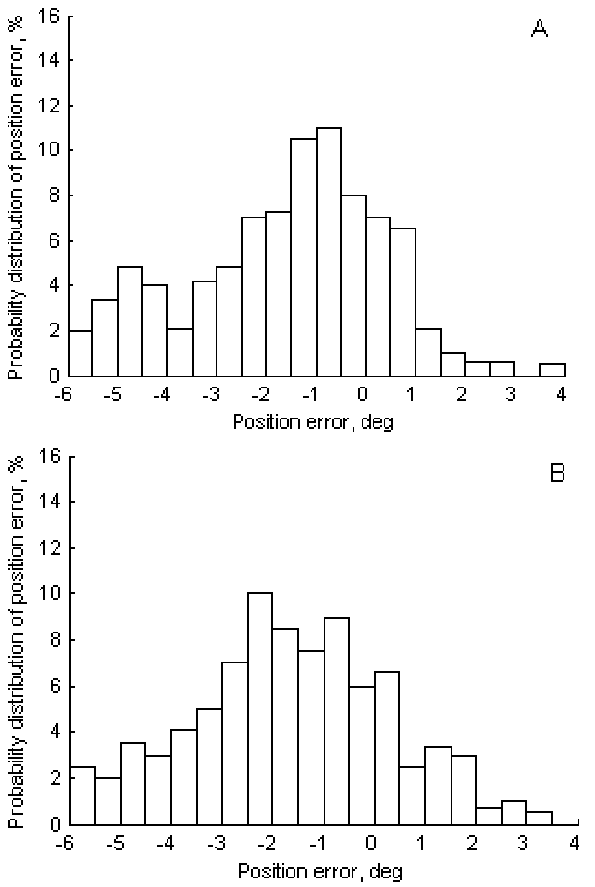

Figure 3. Probability distributions of position errors of the primary saccades for different target amplitudes (A - 10 degrees, B – 20 degrees)

Standard deviations and means of errors after the primary saccades were calculated separately for horizontal and vertical directions σ_{1x}, m_{1x} and σ_{1y}, m_{1y}. Experimental data and information rates I_{1s} calculated by the equation (2) for all five subjects and different target amplitudes are placed in Tables 1 and 2.

Table 1. Experimental and calculated data of the primary saccades executed to the random target jumps with 10 degrees amplitude

Subject	σ_{1x},deg	m_{1x},deg	σ_{1y},deg	m_{1y},deg	I_{1S},bits
GD	1.0	1.0	1.2	1.2	2.3
NR	1.1	1.1	1.3	1.3	2.1
VL	1.2	1.1	1.3	1.4	1.9
DB	1.2	1.0	1.4	1.3	1.8
RZ	1.0	0.9	1.1	1.2	2.4
Average	1.1	1.0	1.3	1.3	2.1

Table 2. Experimental and calculated data of the primary saccades executed to the random target jumps with 20 degrees amplitude

Subject	σ_{1x},deg	m_{1x},deg	σ_{1y},deg	m_{1y},deg	I_{1S},bits
GD	1.5	2.0	1.6	2.2	3.3
NR	1.7	2.1	1.8	2.3	3.0
VL	1.7	2.2	1.9	2.4	2.9
DB	1.6	2.1	1.8	2.3	3.0
RZ	1.5	1.9	1.6	2.2	3.3
Average	1.6	2.1	1.7	2.3	3.1

In Figure 4 the experimental results of the probability distributions of the position errors obtained after complete saccades during fixational micromovements in the horizontal and vertical directions are shown.

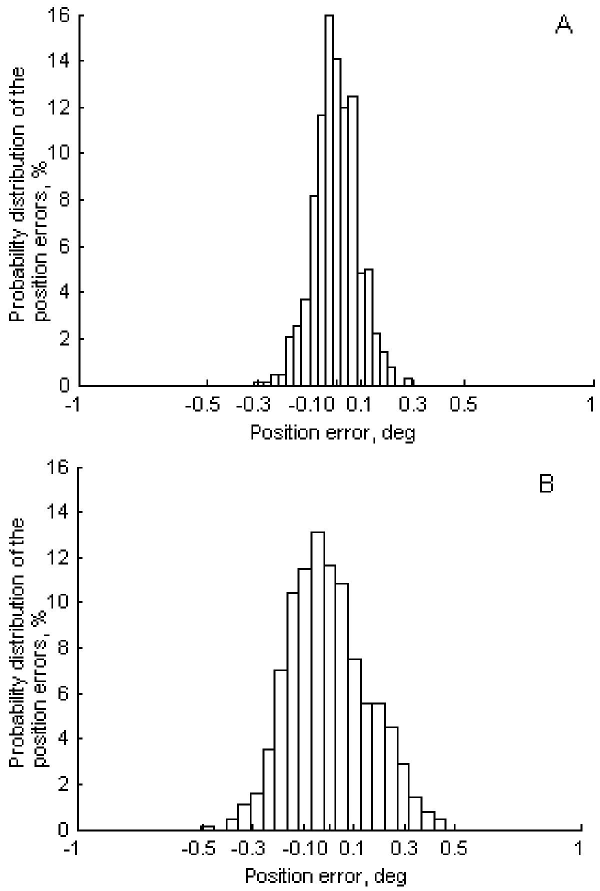

Figure 4. Probability distributions of position errors after complete saccade during fixational micromovements in the horizontal (A) and vertical (B) directions (subject RZ)

The statistical characteristics of the complete double-step saccades executed to the target jumps with intersaccadic interval 1 sec. and amplitudes in the range of 5 – 20 degrees are shown in Table 3. Standard deviations σ_x and σ_y, obtained during the fixation of the final target position, the mean values m_{2x} and m_{2y} of the second step amplitudes and the information rates I_S are there presented. Obtained results illustrate that the average of information rates transferred over oculomotor channel during 1 sec is around 10 bits/sec.

Table 3. Experimental and calculated parameters of the complete double-step saccades executed to the random target jumps with amplitudes in the range of 5 – 20 degrees and intersaccadic interval 1 sec

Subject	σ_x,deg	m_{2x},deg	σ_y,deg	m_{2y},deg	I_S,bits
GD	0.19	1.6	0.21	1.9	9.6
NR	0.15	1.7	0.18	2.0	10
VL	0.18	1.9	0.22	2.5	9.7
DB	0.15	1.6	0.19	2.4	10
RZ	0.10	1.4	0.15	1.8	11
Average	0.15	1.6	0.19	2.1	10

The two-dimensional scatter of position errors during fixational micromovements is shown in Figure 5. It is necessary to point out that this distribution could be assumed as the left uncertainty of the target direction when the eyesight is on the target.

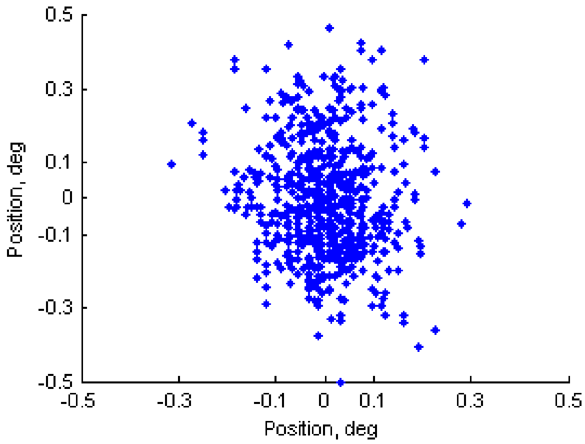

Figure 5. Two-dimensional scatter of the position errors during fixational micromovements

In the next set of experiments we investigated the relationship between the information rates transferred during 1 sec (velocity of the information transferred over channel) and the intersaccadic intervals of the double-step saccadic eye movements. Using equation (4), obtained results of the calculations for all five subjects are placed in Table 4.

Table 4. Information rates transferred over the oculomotor channel during 1 sec as a function of the intersaccadic interval *D*, in bits/sec

D, sec	RZ	NR	AP	GD	AZ
3	3.6	3.8	2.7	3.1	3.3
2	5.8	5.9	4.5	5.3	4.8
1	12	12	8.4	10	10
0.75	12	13	10	12	11
0.5	16	17	13	14	13
0.4	11	10	12	11	14
0.3	7.6	11	9.0	8.3	9.5
0.25	9.5	8.7	8.0	7.5	9.2
0.2	6.9	3.4	7.7	5.7	5.2

The information rates transferred over an oculomotor channel during 1 sec (velocity of the transfer) as function of the intersaccadic intervals are plotted in Figure 6. Most interesting finding of this research reveals that the largest amount of information transferred over the oculomotor channel is around 14 bits/sec and was obtained when intersaccadic intervals are in the range of 0.4 – 0.5 sec. It means that the channel capacity of the control system of the saccadic eye movements is C_s = 14 bits/sec and information could not be sent (obtained) with larger velocity (more quickly) than this threshold value. In other case, channel will loose largest amount of information.

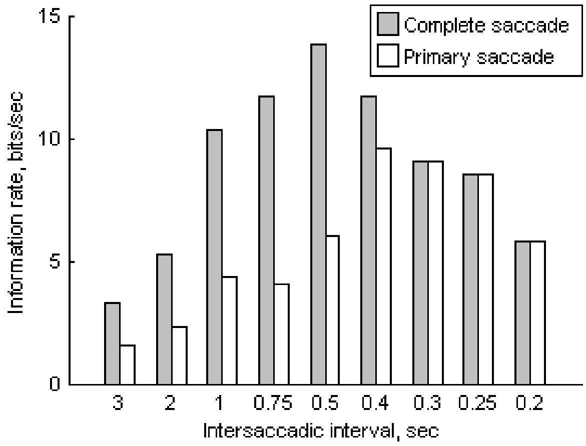

Figure 6. The relationships between the mean values of the information rates transferred over an oculomotor channel during 1 sec and the intersaccadic interval

Speaking in neurophysiology terms, if the positions of the new targets were changed too quickly, the control system of the saccadic eye movements would be no more able to fixate precisely the directions of the appearing targets. Using information theory terms, the eyesight at the offset of saccades (during short fixations) is not precisely on the targets and the uncertainty of the directions of the targets remains large. It is necessary to point out that, when intersaccadic intervals were shorter than 0.5 sec, eyesight, due to saccadic delays (0.2 sec), fixate the targets after its disappearance.

5. Conclusions

Saccadic eye movements traditionally were studied measuring the delay time and the accuracy of eye jumps to the various types of targets. These quantitative parameters differ from the amplitude of the jump and characteristics of the targets. Therefore, the investigation and the evaluation of saccadic oculomotor system measuring input and output parameters, such as time delays and position errors for eye responses, is complicated. The informational evaluation of the target jumps, the lost information after primary and complete saccades, and the amount of the transferred information over oculomotor channel let us determinate saccadic eye movements control system by one more uniform parameter – the channel information capacity. Our theoretical and experimental investigation shows that the channel information capacities are in the range of 14 – 16 bits/sec, obtained at the threshold of the intersaccadic interval *D* = 0.5 sec.

If the intersaccadic intervals D were increased from 1 to 3 sec, the perception and the evaluation of the direction of the target would be better, but the amount of the transferred information over oculomotor channel would be decreased.

Double-step saccades direct the eyesight towards the target and get information about the direction of the target by two steps. During the first steps, primary saccades, which are less accurate, execute the largest part of the movement amplitude but the uncertainty of the direction of the target still remains large. The informational rate transferred over oculomotor channel after primary saccades is around 2-3 bits and depends on the amplitude of the first jump. The amount of information is larger for the bigger amplitudes of the primary saccades despite the larger scatter of position errors for them. This could be assumed because the amplitude ratio with the standard deviation of the position errors remains larger for bigger amplitudes of the primary saccades. Large scatter of position errors of primary saccades could be explained by the low density of position receptors in the periphery of the retina.

Corrective saccades, amplitudes of which are between one and three degrees, direct the eyesight towards the target with high accuracy. The average of the standard deviations obtained during experiments is 0.15 deg in the horizontal direction and 0.19 deg. in vertical. Due to this the uncertainty of the target direction at the endpoint of complete saccade is minimized, which means that the largest part of information transferred over oculomotor channel is made during the corrective saccade. Experimental results demonstrate that the amount of information obtained during corrective saccades is two times bigger than during primary saccades.

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