ON THE DEVELOPMENT OF A DATA BASE FOR SACCADIC PARAMETERS AND MAIN SEQUENCE RELATIONSHIPS – A QUANTITATIVE STUDY OF VIDEO-BASED EYE TRACKING

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Abstract. Video-based eye tracking techniques are a useful methodology for physiological recording of saccades. Saccades are fastest eye movements having the purpose of repositioning the fovea on new target in the visual scene. Laboratory conditions enable stereotyped eye movements and reproducible results that can provide insights into normal and abnormal saccades particularly in neurodegenerative diseases. We discuss the methods and design that produced a consistent normal data set of saccadic parameters and coefficients of main sequence relationships.

Key words: video-based eye tracking, normative data base, saccadic parameter, main sequence relationship.

INTRODUCTION

Saccades are fast, brief, accurate and approximately conjugate eye movements generated by the saccadic subsystem. They have the specific purpose of repositioning the fovea on different parts of the visual scene in order to direct attention to specific regions of interest [17, 19]. Saccades consist of voluntary and involuntary eye movements.

Saccadic eye movements are investigated in the laboratory using different eye-movement recording methods characterized by similar experimental conditions. The subject's head is generally immobilized using a chin rest or bite bar and subject is asked to direct his/her gaze toward a visual stimulus, often a luminous spot, on a colour and luminance homogeneous background. Although eye movements are recorded in the laboratory under conditions different from those in which normal saccadic eye movements are generated, with the head free to move and a visual environment rich in stimuli, laboratory conditions enable stereotyped

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movements and reproducible results that can provide insights into normal saccades and abnormal saccades such as those associated with neurodegenerative diseases [17, 23]. Saccades may be classified according to how they are evoked during laboratory tests, among which visually-guided saccades are involuntary eye movements made in response to the appearance of a visual stimulus.

The numerous methods for saccade recording include electrooculogram (EOG) in which electrodes placed around the eyes are used [7]; magnetic search coil using scleral contact lens [21]); infrared reflection detectors in which reflexes from the pupil or limbus, the boundary where the white sclera joins the colored iris, are detected [4, 11]. The recording method developed most recently is the video-based eye tracking technique, which involves combined pupil and corneal reflex detection by means of a video-camera. These instruments simultaneously measure two optical characteristics of the moving eye: the bright corneal reflection and the bright pupil. They are based on extrapolation of the "point of regard", which is the gaze point in space and utilize new computer vision techniques for the identification of edges and contours of the eye anatomical structures. The most recent device is based on the dual Purkinje images corneal reflections, founded on the principle that light bouncing off the eye produces a series of reflections. The first and brightest is corneal reflection, the second image is reflected off by the rear surface of the cornea and the other two from the front and rear of the lens. The four Purkinje images have different motions depending on eye rotation. The dual Purkinje image eye tracker measures the disparity between the first (corneal) and the fourth (lens) images, the degree of which is directly related to eye rotations [8, 9, 20]. Video-based eye trackers are not invasive and are fairly accurate. The horizontal and vertical eye movements are detected with a high temporal and spatial resolution: the recorded signal is sampled from 60 Hz to 300 Hz, and recently 1000 Hz; the resolution is about 0.01° RMS; the average accuracy is about 0.5°; the gaze range is 30° on vertical and 40° on horizontal direction.

Previous studies about descriptive parameters of saccades developed and used different normative database. Data from different recording systems was compared. However, the definition of a consistent set of normative saccadic parameters usable for intra and inter laboratory comparisons may be difficult.

The clear definition and knowledge about technical properties of registration systems (range of linearity, recording band, attempted head movement, lens slippage) allows to identify the precautions to be used to avoid distortion in the signal recorded with respect to the real trajectory of the saccadic movement. It also makes possible the comparison of the data obtained with different equipments. However, in the case of the signal processing, the properties of saccadic parameters depend on the frequency of sampling, digitization and processing procedures applied, like computation defining the velocity of eye movements [12, 13]. In detail, the cut-off frequency of low-pass filtering applied to the digitized signal of eye position, overall bandwidths of the algorithm used to compute the eye velocity

and acceleration have to be considered. To determine the beginning and the ending of the saccades, correct criteria need to be adopted; in addition in order to fit correctly the saccade parameters relationship, laws and rules have to be evaluated. Finally, homogeneous samples (sex and age) of healthy subjects have to be recorded, and standardized procedures for testing subject's performances should be designed.

In this study, we set out saccade parameters and their relationship, after looking carefully at processing, selection, and checking of the saccadic eye movement recorded with a video-based eye tracking technique. We aim to provide a reliable normative database for human saccadic parameters and coefficients of main sequence relationships that could be compared to the results obtained with other recording techniques. We also compare our results with a previously published set of data to evaluate the consistency of quality of estimation within and between test centres.

MATERIALS AND METHODS

SUBJECTS

Forty healthy subjects (mean age: 35.2 years; range: 30 to 68 years) took part in the study. The subjects did not have past events of neurological or eye problems, did not use addictive substances and were not running pharmacological treatments for neurological or eye diseases. They gave their informed consent and the study was approved by the Regional Ethics Committee.

RECORDING METHODS AND EXPERIMENTAL DESIGN

An ASL 504 eye-tracker device (Applied Science Laboratories, Bedford, MA, USA) was used to record horizontal and vertical components of eye movements. Real-time software was used to acquire data. Recorded data were sampled at a frequency of 240 Hz, encoded in binary digital form with 16-bit resolution and stored. All recordings were conducted in complete darkness and in subjects with head immobilized by a bite bar and chin rest.

The visual target was presented on a 31 × 51 cm LCD screen (resolution: 768 × 1024 pixel; frame rate: 60 Hz). The target was a red dot (diameter: 0.4° of visual angle; luminance: 63 cd/m^2) shown on a black background (luminance: 2.5 cd/m^2). A distance of 72 cm from subject's eyes to screen was used.

Horizontal visually-guided saccades to targets located eccentrically from 6° to 20° (constant increase of 2°) were tested. After a procedure of calibration, performed with nine static points disposed in central, horizontal, vertical and oblique positions of the screen, a visual target jumped from a central fixation point

to a right or left point in a random way. The time interval ranged from 1500 ms to 2000 ms. Each test consisted in a sequence of 20, 40 or 60 trials.

DATA ANALYSIS

A semi-automatic algorithm was developed to perform post-processing off-line analysis. Recorded data were filtered to remove blinks using a numerical threshold to check signal of horizontal and vertical eye position and a linear interpolation was used to replace data. The data was filtered using a third-order Butterworth low-pass digital filter with a cut-off frequency of 25 Hz (–3 dB). We did not find appreciable effects of the signal processing between filtered and original position signals. Eye velocity and acceleration computation were based on the following derivative algorithm:

$$\dot{f}(i) = \frac{1}{T}\sum_{n=1}^{4} c_{\mathrm{n}}[f(i+n) - f(i-n)] \tag{1}$$

where T is the sampling period, i is the current point in time, n is an integer representing the step size in number of point in time, c_{n} is the coefficients and $f(i)$ is the function at time i. We set the upper limit of n to 4 in order to obtain a eight-point central difference derivative algorithm with a bandwidth greater than 70 Hz at the digitization frequency that we were using (240 Hz) [10, 12]. The start and end of the saccadic eye movements were determined applying a numerical threshold of 10°/s on velocity signal. After revelation of fast eye movements and extraction of their features, a classification procedure was used to find saccadic eye movements. Finally, an interactive procedure was used to correct the automatic selection of each saccade. We performed a visual inspection of recorded signal to check all automatically selected saccade sections and we eliminated any selection that did not correspond to saccadic eye movement.

Quantitative analysis of descriptive parameters of the saccade dynamic properties and metrics were carried out for each subject. The dynamic properties of saccade were described by parameters of duration, peak and mean velocity, peak acceleration and deceleration. Saccade metrics were described using the parameters of amplitude and accuracy, evaluated using saccade gain and endpoint error. The means of all saccadic parameters mentioned above were calculated for each test of each patient, in respect to the representative target distances of 10° and 18°. Finally, the analysis was finalized to describe the relationships between saccade dynamic and metric parameters by useful tools of main sequence relationships (see chapter Results and Discussion). To determine the accuracy of applied models on the entire dataset, model prediction was evaluated using percentage root mean square error (*PRMSE*), where small values of this parameter indicate good fit.

All analysis algorithms, computations and regressions were performed using Matlab software (The MathWorks Inc., Natick, MA, USA).

RESULTS AND DISCUSSION

We performed a quantitative analysis of the traditional descriptive parameters [5] of saccade dynamics and metrics for the first saccade made by subjects after visual target presentation. In detail, we focused on evaluation of their relationships.

SACCADE DYNAMICS

We described the dynamic properties of saccade trajectory by duration, velocity and acceleration. All these saccadic parameters depended on the magnitude of eye movement.

Saccade duration was the time interval between the start and the end of the eye movement. Generally the start and end times are determined using a velocity threshold and define the time interval in which the velocity of movement exceeds the threshold. Typical threshold values reported in the literature range from 5°/s to 40°/s [3, 24]. We set a threshold of 10°/s (see Chapter Materials and Methods) in order to accurately detect and include the entire excursion of saccadic eye movements from slower starting phase of movement to its ending.

Saccade duration (D) was significantly correlated with amplitude ($p<0.001$) and increased as a function of amplitude (A); the function is known as the main sequence relationship [4] and is approximately linear for saccades from 5° to 50° [17]. We assessed the relation between the main sequence of duration *versus* amplitude using the following model:

$$D = D_c + \alpha \times A \tag{2}$$

where D_c is the intercept with time-axis and α is the slope representing the increment of duration with respect to amplitude in degrees of visual angle. Figure 1 shows the main sequence relationship between duration and amplitude using the linear model on data of all healthy subjects. The data base we analysed, obtained by forty healthy subjects who participate to the study, indicated a D_c of 28 ms and a α of 2.2 ms/° (*PRMSE* = 17%). Our results matched those previously reported in the literature, carried out by other eye recording methods. Values estimated from published data indicate a range from 20 ms to 30 ms for D_c and a range from 1.5 ms/° to 3 ms/° for α [28].

Regarding the value of D_c and α that we estimated, for saccades of less than 5°, the duration increases with increasing amplitude more quickly than the linear relationship and obeys a power law. The power law indicates that for very small eye movements, like microsaccades with amplitude of less than 0.5°, the duration

may be equal to zero. Although only a few studies have examined very large saccades, those with amplitude greater than 60° obey the linear relationship between duration and amplitude up to the physical limit of eye motility.

We found a mean duration of 48 ± 4 ms and 65 ± 4 ms for the two representative target distances of 10° and 18°, respectively. We selected the value of two target distances representing the average behaviour of small and large saccades in the normal amplitude range of the physiological saccadic eye movement.

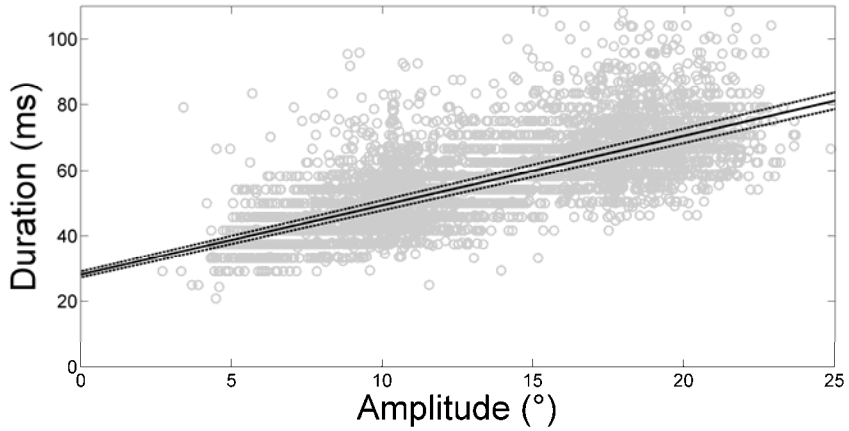

Fig. 1. Plot of main sequence relationships of saccade duration *versus* amplitude of healthy subjects (○ light gray points). The data was fitted using the equation (2). The broken curves indicate the 95% prediction bounds for the fitted coefficients.

Saccade velocity was measured using peak and mean velocity. Peak saccade velocity (V_{peak}) was the maximum eye velocity, in degrees of visual angle/second, of a saccade.

Peak saccade velocity was significantly correlated with amplitude (p<0.001) and increased as a function of amplitude; this function too is known as the main sequence relationship [4]. We assessed the relation between the main sequence of peak velocity *versus* amplitude using an exponential model (Eq 3) that reflects progressive saturation of the relationship for large saccades. The saturation of peak velocity is generally complete for saccades greater than 50°. We also found that data was well represented by the linear model seeing as the relationship was approximately linear for saccades of less than about 20° [17].

$$V_{peak} = V_{peakmax} \times (1 - e^{(-A/C)}) \tag{3}$$

where $V_{peakmax}$ is asymptotic peak velocity and C is the angle constant shaping the exponential rise. Our data base showed a $V_{peakmax}$ of 596.6°/s and a C of 10.4 (*PRMSE* = 15%). The data reported in the literature indicate a $V_{peakmax}$ of about

500°/s, although human saccades can have a velocity up to 600°/s [19] and C is generally indicated close to 10 [22]. Figure 2 shows the main sequence relationship between peak velocity and amplitude using the exponential model on data of all healthy subjects.

The relationship described above is for saccades with amplitudes of more than 5°. For smaller saccade amplitudes, the relationship between velocity and amplitude is continuous and both linear and power-law curves, based on reported data of microsaccades with amplitude greater than 0.04°, appropriately describe the relationship between velocity and amplitude [1, 18].

Average peak velocity was 380 ± 41°/s for 10° of target distance and 508±58°/s for 18°of target distance.

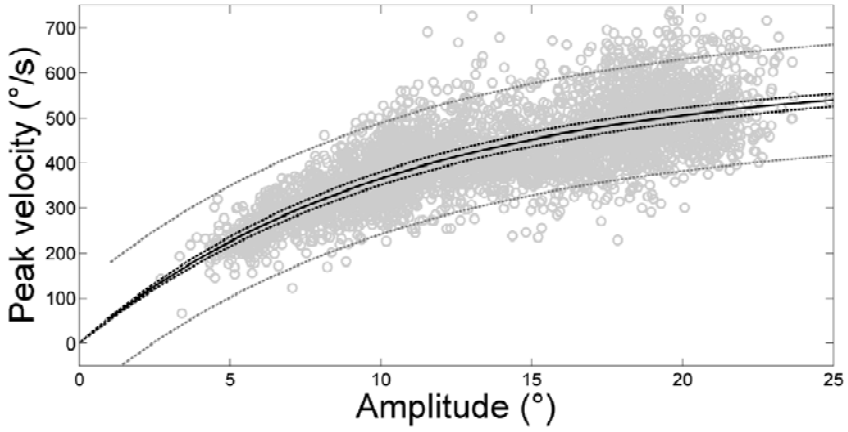

Fig. 2. Plot of main sequence relationships of peak saccade velocity *versus* amplitude of healthy subjects (○ light gray points). The data was fitted using the exponential equation (3). The black broken curves indicate the 95% prediction bounds for the fitted coefficients. On all data of healthy subjects, 5% and 95% prediction intervals for new observations are shown (dark gray broken curves).

Mean saccade velocity (V_{mean}) was the ratio of saccade amplitude to duration, measured in degrees of visual angle/second. By mathematical definition, we calculated directly the mean velocity from saccade duration and amplitude. Mean velocity therefore depended on these two parameters. Like peak saccade velocity, we described the relationship between mean velocity and amplitude by the following equation:

$$V_{\text{mean}} = \frac{V_{\text{meanmax}} \times A}{A_{\text{cm}} + A} \tag{4}$$

where V_{meanmax} is the asymptotic limit of mean velocity and A_{cm} is the amplitude where the half of asymptotic limit of mean velocity is reached. We found a V_{meanmax} of 472.4°/s and a A_{cm} of 14°. Typically, V_{meanmax} ranges from 350°/s to 500°/s and A_{cm} ranges from 10° to 20°, values estimated from published data [5].

We found an average mean velocity of 201 ± 21°/s for 10° of target distance and 271 ± 24°/s for 18°of target distance.

Unlike saccade duration measurements, measures of saccade velocity, specifically peak velocity, are independent of specific thresholds used for the identification of saccadic eye movements, for example thresholds of velocity or position used to determine the beginning or end of the movement. This is why the parameter velocity has been chosen to determine the influence of physiological, psychological, pharmacological or clinical conditions on intrinsic characteristics of saccadic eye movements. Moreover, reduced velocity may be linked to central or peripheral neurological diseases [17].

Peak saccade velocity and mean saccade velocity were related in a linear manner (p<0.001). We calculated this relationship using the ratio of peak velocity to mean velocity (Q_{ratio}) [16]. The data base of our healthy subjects indicated an average Q_{ratio} of 1.85 ± 0.08 that ranged from 1.79 to 1.88, for saccades with an amplitude in the range 6–20°. Our results matched the values estimated from published data that report an average Q_{ratio} of 1.6 with a range of 1.38–1.90 in saccades with amplitudes in the range 5–50° [5]. We also assessed the relation between peak velocity and mean velocity using the following model:

$$V_{peak} \times D = Q_{coef} \times A \tag{5}$$

where $V_{mean}=A/D$ and Q_{coef} is the slope representing the increment of peak velocity with respect to mean velocity. Our data base indicated a Q_{coef} of 1.77 ($PRMSE$ = 12%). Prior reported data indicate a value ranging from 1.69 to 1.83 [26]. Figure 3 (up) shows the velocity waveform of a representative healthy subject, the Q_{ratio} of peak velocity and mean velocity can be observed.

The Q_{ratio} can be used to examine the skewness (asymmetry) of the velocity profile, a value of Q_{ratio} of 2 is calculated for a triangular profile of velocity [16]. Velocity waveforms of small saccades, usually about 10°, are roughly symmetrical, meaning that peak velocity is about halfway between the beginning and the end positions of the saccade. Larger saccades show a decrease in skewness, meaning that peak velocity is closer to the beginning than to the end position of the saccade.

Saccade acceleration was the rate of change of saccade velocity in time, in degrees of visual angle/seconds^2. Saccade acceleration was evaluated separately for the acceleration and deceleration phases. Saccade acceleration was evaluated using the acceleration time, that was the time interval between the start of the eye movement and peak velocity, and initial peak acceleration, that was maximum eye acceleration. Saccade deceleration was evaluated using the deceleration time, that was the time interval between peak velocity and the end of the eye movement, and peak deceleration, that was maximum eye deceleration.

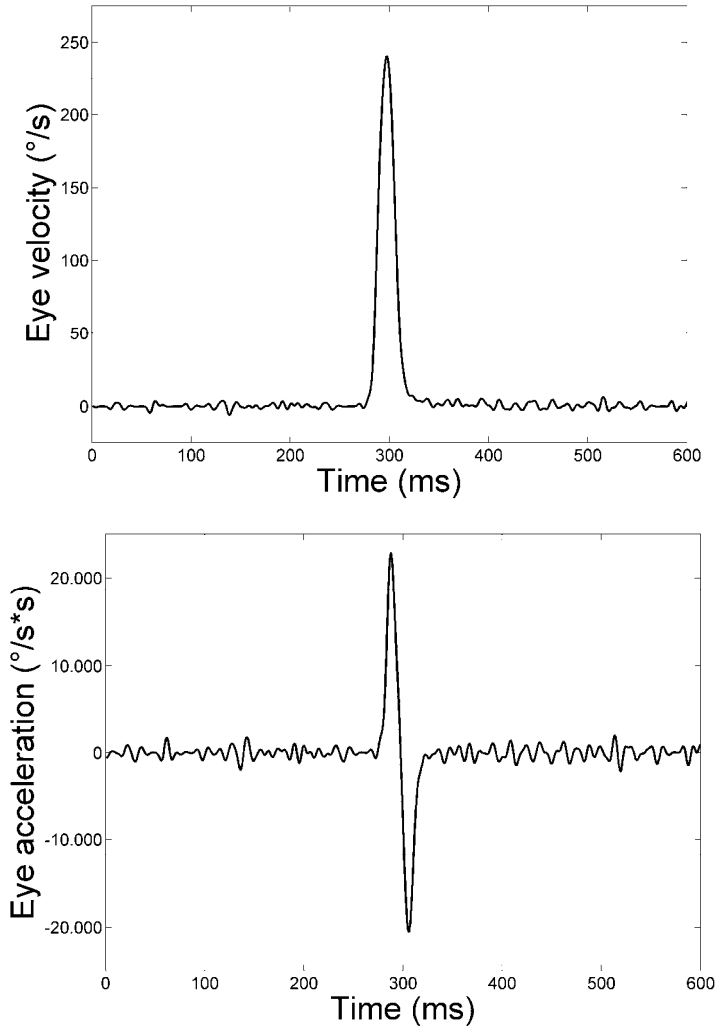

Fig. 3. Example of (up) velocity waveform (eye velocity *versus* time) and (down) acceleration trace (eye acceleration *versus* time) of a 5° horizontal saccade by a healthy subject.

We found an acceleration time of 21 ms and a deceleration time of 28 ms. Peak acceleration was about 21,000°/s^2 in saccades of 10° and 25,000°/s^2 in saccades of 18°. Peak deceleration was about 22,000°/s^2 in saccades of 10° and 25,000°/s^2 in saccades of 18°. Previous studies report an acceleration time that ranges from 20 ms in saccades of 10° to 40–50 ms in saccades of 40° [5]. Peak acceleration is about 30,000°/s^2 in saccades of 10° and 35,000°/s^2 in saccades of 15° [3]. Figure 3 (down) shows an example of eye acceleration recorded in a representative healthy subject.

The skewness of the velocity waveform between acceleration and deceleration phases depended on saccade amplitude. In saccades with almost symmetrical velocity profile, i.e. small saccades of about 10°, the duration of the acceleration phase was equal to the duration of the deceleration phase. Larger saccades were more skewed and the duration of the acceleration phase was less than that of the deceleration phase.

Saccade duration and velocity vary with many factors. Initial eye position in the orbit and orientation of eye movement cause variations in parameters: centrifugal saccades have longer duration and lower velocity than centripetal saccades [14], while there is apparently no difference in velocity and duration between adducted and abducted saccades for the same eye. Presence or absence of a visual stimulus, size of target, predictability of stimulus movement and nature of the stimulus itself modulate saccade dynamic performance [6]. Finally, other factors that modulate duration and velocity are age, alertness and attention or fatigue [25, 27].

SACCADE METRICS

Saccade metrics was described using the parameters of amplitude and accuracy. Accuracy was evaluated using saccade gain and endpoint error, and like dynamic saccade parameters, depended on the magnitude of eye movement.

Saccade amplitude was the difference, in degrees of visual angle, between eye position at the start and end of the saccade. We estimated a mean amplitude of 9.8 ± 0.6° for a target distance of 10° and 17.6 ± 0.7° for a target distance of 18°. The amplitude distribution showed a single peak at a saccade amplitude of 10° in healthy subjects. A similar distribution was observed for 18° with a single peak at 18° saccade amplitude. The percentage of saccades undershooting 10° and 18° target distances, by about 10%, was about 13% for both target distances; values estimated from 25 representative healthy subjects [10].

Natural human saccades usually have an amplitude of 18° or less [2]; larger gaze shifts occur as a combination of a head and eye movement. Under experimental conditions, large saccades are encouraged by immobilizing the head by means of a bite bar or chin rest and instructing the subject to track a visual stimulus on a plain background. In this case, saccades of 2–60° can be performed. The amplitude of saccadic eye movements is inaccurate and variable. Previous studies on normal subjects, performing habitual saccades, have suggested that, when target displacement is greater than 10°, saccades undershoot it by about 10% of target eccentricity. After a latency of about 100–150 ms, initial hypometric saccades that fall short of the target are followed by a secondary corrective saccade to align the fovea with the target [6, 15], if their end positions are not sufficiently near the target. However, the purpose of hypometria is not well established.

Saccade accuracy, or complementary saccade error, of goal directed eye movements was the difference between final eye position after the first saccade and the position of the visual stimulus. We evaluated accuracy in terms of saccade gain and endpoint error.

Saccade gain was the ratio of the initial saccade amplitude to target distance. Average gain was 0.98 ± 0.06 and 0.94 ± 0.04 for saccades to targets at 10° and 18°, respectively, on the data base of subjects that we studied. Since estimation of saccade gain may be subject to error cancellation due to hypometric and hypermetric saccades in individual subjects, endpoint errors were estimated to improve saccade accuracy.

Saccade endpoint error (e) was defined as the difference between target position (T) and end position (P) of the first saccadic eye movement, in degrees of visual angle.

$$e = T - P \tag{6}$$

Using this equation, undershoot had positive endpoint errors and overshoot had negative endpoint error values. We considered appropriate to use the following equation to characterize dysmetria:

$$e = |T - P| \tag{7}$$

where absolute error was defined as the modulus of the angular distance between target position and final eye position of the initial saccade. We found an endpoint error of 0.88 ± 0.30° for 10° target distance and 1.49 ± 0.51° for 18° target distance. Saccade endpoint errors is correlated with target distances and increased with increasing target distance. Previous studies, comparing 10° and 18° saccades in healthy subjects, show an increase in absolute error of 0.53° [10].

CONCLUSIONS

The goal of this research was the development of a valid normative data base for human saccade recorded with the recent video-based eye tracking technique. Therefore, we tried to get accurate and consistent data with the aim of using it for clinical application and diagnosis of neurological diseases. Analogously to the previously reported normative data base, we also introduced a set of data representing the coefficients of relationships between saccade parameters, that allow to use the powerful tools of main sequence for studying saccadic eye movements. We expect that given this combination of data, it will be useful not only for improving basic research, but also for the application of the saccade analysis in clinical context. Finally, we also encourage the diffusion of video-based eye tracking technique, between clinicians and neuroscientists, as inexpensive and reliable methods for clinical and basic research applications.

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