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SacLab: A toolbox for saccade analysis to increase usability of eye tracking systems in clinical ophthalmology practice

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ABSTRACT

Purpose: Many open source software packages have been recently developed to expand the usability of eye tracking systems to study oculomotor behavior, but none of these is specifically designed to encompass all the main functions required for creating eye tracking tests and for providing the automatic analysis of saccadic eye movements. The aim of this study is to introduce SacLab, an intuitive, freely-available MATLAB toolbox based on Graphical User Interfaces (GUIs) that we have developed to increase the usability of the ViewPoint EyeTracker (Arrington Research, Scottsdale, AZ, USA) in clinical ophthalmology practice.
Methods: SacLab consists of four processing modules that enable the user to easily create visual stimuli tests (Test Designer), record saccadic eye movements (Data Recorder), analyze the recorded data to automatically extract saccadic parameters of clinical interest (Data Analyzer) and provide an aggregate analysis from multiple eye movements recordings (Saccade Analyzer), without requiring any programming effort by the user.
Results: A demo application of SacLab to carry out eye tracking tests for the analysis of horizontal saccades was reported. We tested the usability of SacLab toolbox with three ophthalmologists who had no programming experience; the ophthalmologists were briefly trained in the use of SacLab GUIs and were asked to perform the demo application. The toolbox gained an enthusiastic feedback from all the clinicians in terms of intuitiveness, ease of use and flexibility. Test creation and data processing were accomplished in 52 ± 21 s and 46 ± 19 s, respectively, using the SacLab GUIs.
Conclusions: SacLab may represent a useful tool to ease the application of the ViewPoint EyeTracker system in clinical routine in ophthalmology.

1. Introduction

In our everyday lives, we regularly make various types of eye movements because of the activity of three pairs of antagonistic muscles that support each eye. Saccades are rapid conjugate movements of the eyes as they jump from fixation on one point to another, bringing an object of interest into focus on the fovea. Their amplitude can range from the small movements made while reading to the wide movements made while scanning the surrounding environment [1]. Since saccades are the result of the joint action of the visual, oculomotor and central nervous systems, saccadic abnormalities can be seen in a wide variety of disease states [2].

In recent years, the increasing number of reliable Eye Tracking (ET) systems has raised growing interest in studying eye movements and gaze patterns on a quantitative basis [3–5], which is replacing the previous, purely qualitative approach [6,7]. Particularly, video-based ET systems have become more and more popular because of their non-invasive nature, the rapid progress in electronic data processing and their continuous fall in prices [6,8,9]. Moreover, the results obtained with video-based ET systems have been proved to be comparable with those provided by well-established, more invasive systems used for research purposes, such as scleral search coils [10,11]. In the past, a non-invasive solution for tracking the eye movements (CENOG system), based on the use of four small skin electrodes attached around each eye and small voltages measurements by these electrodes, was proposed by Ledley et al. [12]. However, this system had little impact since no further evidence of applications in research or clinical fields can be found.

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Therefore, the video-based ET systems remain the most promising approach for the non-invasive quantification of eye movements.

Despite ET systems can be powerful non-invasive tools, they usually require considerable amount of time for setting the system and creating the ET tests, as well as some programming skills for post-processing analysis of the recorded data [13,14].

Recently, many free software packages have been developed to be used with video-based ET systems [13–17]. However, they have been mainly addressed to neurological and psychophysiological research and none of these is specifically designed to encompass in a single package all the main functions required for carrying out an ET test, from the creation of the visual stimuli test, to the automatic aggregate analysis of the recorded data.

In this paper we introduce SacLab, a new MATLAB toolbox that we have developed for the analysis of saccadic eye movements while using a commercial eye tracker, the ViewPoint EyeTracker by Arrington Research, without requiring that users have programming skills and knowledge. Our aim is to provide a tool that may simplify the use of the ViewPoint ET system, in order to encourage the introduction of this technology in the clinical ophthalmology practice.

2. Methods

SacLab is based on intuitive Graphical User Interfaces (GUIs) and automatic processing functions for the analysis of saccades. These functions work on raw data collected by commercially available ET systems. Raw data are typically a set of x and y coordinates for each eye (*Gaze Point*), which represent the horizontal and vertical positions of the subject's gaze on a screen on a normalized scale (using the screen size as reference).

The SacLab software is composed of 4 modules: Test Designer (TD), Data Recorder (DR), Data Analyzer (DA) and Saccade Analyzer (SA). These modules allow to perform all the operations required to carry out an ET test for the analysis of saccades, starting from the creation of visual stimuli tests to the analysis of saccadic parameters collected from multiple recordings. SacLab has been developed in MATLAB environment and it is compatible with every operating system that supports MATLAB (Microsoft Windows, Mac OS and Linux). In this first version, SacLab has been developed to be interfaced to the ViewPoint EyeTracker Binocular SceneCamera System (Item BSU07), a commercial ET system manufactured by Arrington Research (Scottsdale, AZ, USA).

The functions of each SacLab module and communication functions with the native ViewPoint ET software are summarized in Fig. 1, and described in detail in the following paragraphs.

A periodically updated version of the SacLab source code will be made available on the Mathworks File Exchange Central.

From SacLab Startup Window (Fig. 2) each SacLab module (TD, DR, DA, SA) can be accessed. By pressing the SacLab Startup icon provided in the GUI of each SacLab module, the SacLab Startup Window can be recalled or it is automatically recalled when a SacLab module is closed by the user.

2.1. Test Designer (TD) module

TD module allows to quickly and easily create the visual stimuli tests to elicit saccadic response in the subject under examination, without requiring the user to have experience with graphic editors. A visual stimuli test is a series of images showing a target, which changes its position on the screen; the subject is asked to look at the moving target to elicit saccades of different amplitudes, while the eye movements are recorded by the ET system.

TD module allows to set all the features of the desired visual stimulus image, including background color, target size, target shape and target position on the screen (*Stimulus Data functions)*.

Other functions (*Geometry Data functions*) are provided to set all the features (screen size, screen resolution, aspect ratio, viewing distance) required to calculate the target position, i.e. to convert it in pixels, within the created stimulus images. The order of the stimulus image presentation can be changed by selecting the desired image from a created image list and by applying “add”, “delete” and “modify” functions to the image list (*Image List functions*). Also the duration for each image presentation can be set.

A collection of newly created stimulus images can be saved in a *Test File* or a previously created *Test File* can be loaded (*File Management functions*) to be used for the ET test.

A preliminary library of standardized diagnostic tests for the analysis of saccadic movements, which may underlie pathologies involving disturbances of oculomotor behavior in various gaze directions (tests for horizontal, vertical and oblique saccades) has been prepared, following suggestions from ophthalmologists and taking as reference some previous works in the literature [3].

The output *Test File* provided by the TD module contains information on both stimulus data and geometry data, as well as software command lines to load the created stimulus images and show them on the screen.

The GUI of TD module is reported in Fig. 3.

Screen (monitor) size, screen resolution and viewing distance can be set in the top-right corner of the GUI (functional block **2**). Features of the stimulus images (color, target size, target shape and position) can be set using the controls in the bottom section of the GUI (functional block **1**). The image list and timing for image presentation on the screen can be managed in the box on the right side of the GUI (functional block **3**). The created stimulus image is displayed in real time in the white central box of the GUI (functional block **5**). By pressing the ‘SAVE TEST FILE’ button in the bottom-left corner of the GUI (functional block **4**) the created visual stimuli test can be saved, or by pressing the ‘LOAD TEST FILE’ button a previously created visual stimuli test can be loaded.

2.2. Data Recorder (DR) module

DR module allows to record eye movement data by implementing the communication with the native ViewPoint ET software. DR functions allow to load or unload a visual stimuli test created with TD module (*Test functions*) and to start data recording (*Recording functions*). The DR module implements functions for a two-way communication between SacLab and the native ViewPoint ET software (*ET communication functions)*. This two-way communication takes place through dedicated MATLAB libraries provided by the native ViewPoint software (Fig. 1). In details, DR module sends inputs for various functions that are managed by the ViewPoint software (i.e. calibration, setting of the viewing distance, loading/presentation of the stimulus images created with the TD module). Particularly, the stimulus image presentation is managed by ViewPoint software and its timing is stored by ViewPoint and then retrieved by DR module during data recording in order to ensure the highest possible accuracy of timing for stimulus presentation.

The above functions are essentially duplicates of the native ET software functions, but we provided all of them also in the DR module frontend to allow the user to manage them from a single interface. The DR module frontend can be used simultaneously with the ViewPoint frontend or as a stand-alone window. However, we recommend, while using the DR module, to check the ViewPoint frontend in order to see if the native ET software is working as desired.

On the other hand, the ViewPoint software sends the acquired eye movement data to DR module for data recording and further data analysis.

Via the graphical interface of DR module, the user can select the eye movement data (*Eye Data*) that will be recorded, by choosing from a list of recordable *Eye Data* available in the native ViewPoint ET software *(Eye Data selection functions*). See Table 1 for the set of

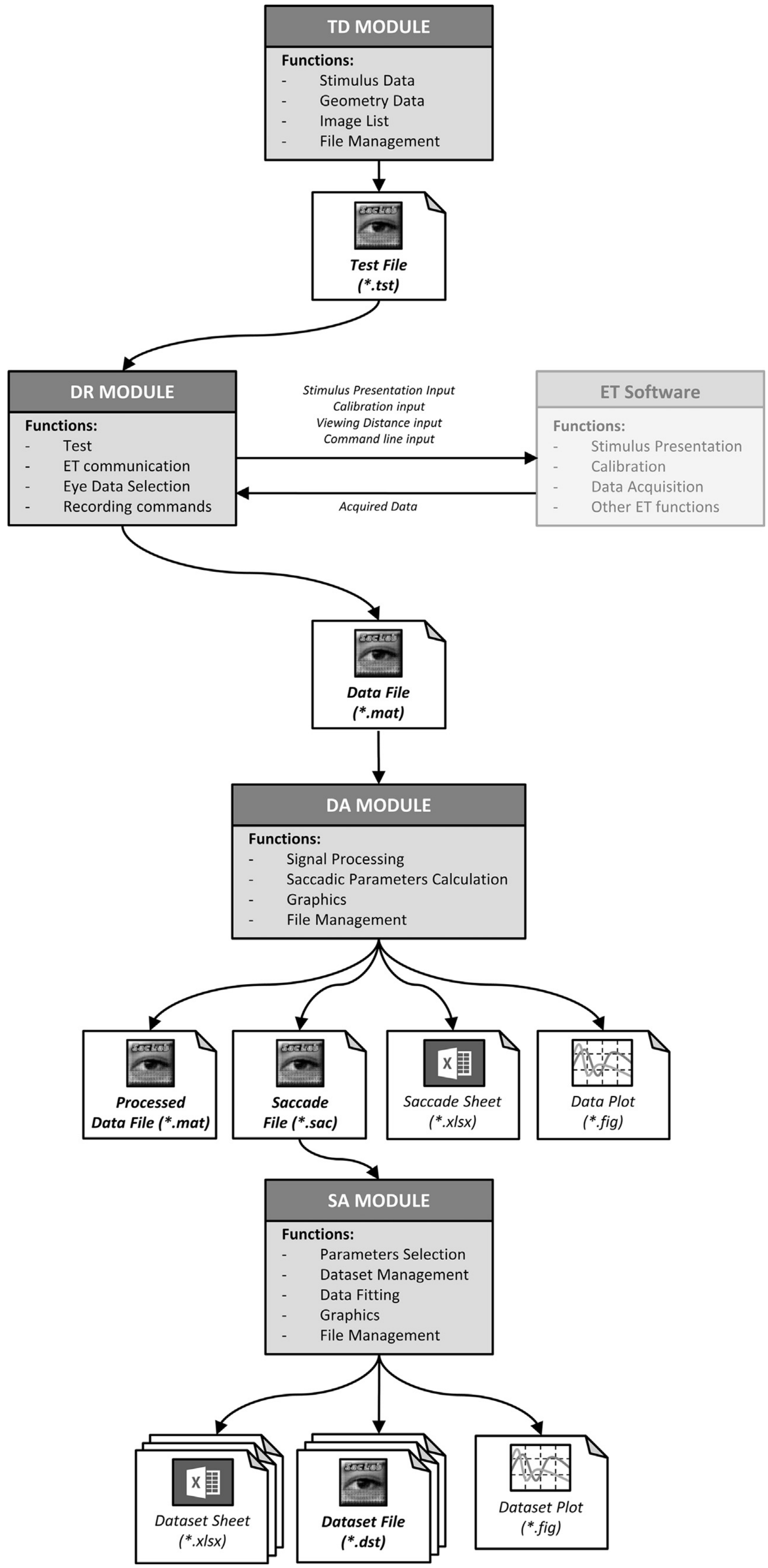

Fig. 1. SacLab framework: the four SacLab modules (TD, DR, DA, SA) in dark grey boxes and their interaction with the native ET software (light grey box). A list of software functions is included in each grey box, while the software output files are reported in white boxes.

Fig. 2. SacLab Startup Window: SacLab icon (top) and the buttons for launching the TD, DR, DA, SA modules (bottom).

recordable *Eye Data*. At the end of data recording, the DR module saves the data retrieved by the ViewPoint in a *Data File* (*.mat extension) that contains the *Eye Data* organized in the following array structures: 1) *Time Reference,* that is an array containing the acquisition time of each recorded sample (one Time Reference array for each eye). 2) *Recorded Eye Data*, that is a series of arrays containing all the recorded samples for the selected *Eye Data*, stored separately for each eye. If the selected *Eye Data* have two components (e.g. *Azimuth Angle* and *Elevation Angle*, for *Gaze Angle Eye Data*), a couple of arrays will be stored for each eye. Using the *Time Reference* arrays, each value of the *Recorded Eye Data* arrays can be easily referred to the corresponding acquisition time. 3) *Expected Gaze Values,* that are two couples of arrays (*Expected Gaze Point* and *Expected Gaze Angle*) that contain the position (expressed as normalized X, Y coordinates or Azimuth, Elevation angles, respectively) of the target stimulus image retrieved from the *Test File*. The *Expected Gaze Values* arrays, which have the same structure as *Gaze Point* and *Gaze Angle Recorded Eye Data* and are referred to the same *Time Reference* arrays, are used to evaluate the subject's performance with respect to the target stimuli in the loaded test.

Typical size of a Data File, considering the sampling frequency of 60 Hz and assuming that both eyes and all parameters are selected for data collection, is 14.52 kB per second of data acquisition.

The GUI of DR module is reported in Fig. 4.

By pressing the ‘LOAD TEST’ button in the central section of the GUI (functional block **1**), the visual stimuli test created using the TD module can be loaded. The Eye Data of interest can be selected using the checkboxes in the top section of the GUI (functional block **3**) before starting the recording of the eye movements captured with the ViewPoint ET system. Calibration of the ET system is performed by pressing the ‘CALIBRATE’ button in the bottom section of the GUI (functional block **2**). Running of the loaded test and the synchronous Eye Data recording are activated by pressing the ‘START’ button in the top-right corner of the GUI (functional block **4**). Data recording is terminated automatically when the visual stimuli test is over, or it can be controlled manually (by pressing the ‘STOP’ button) in case of errors during recording.

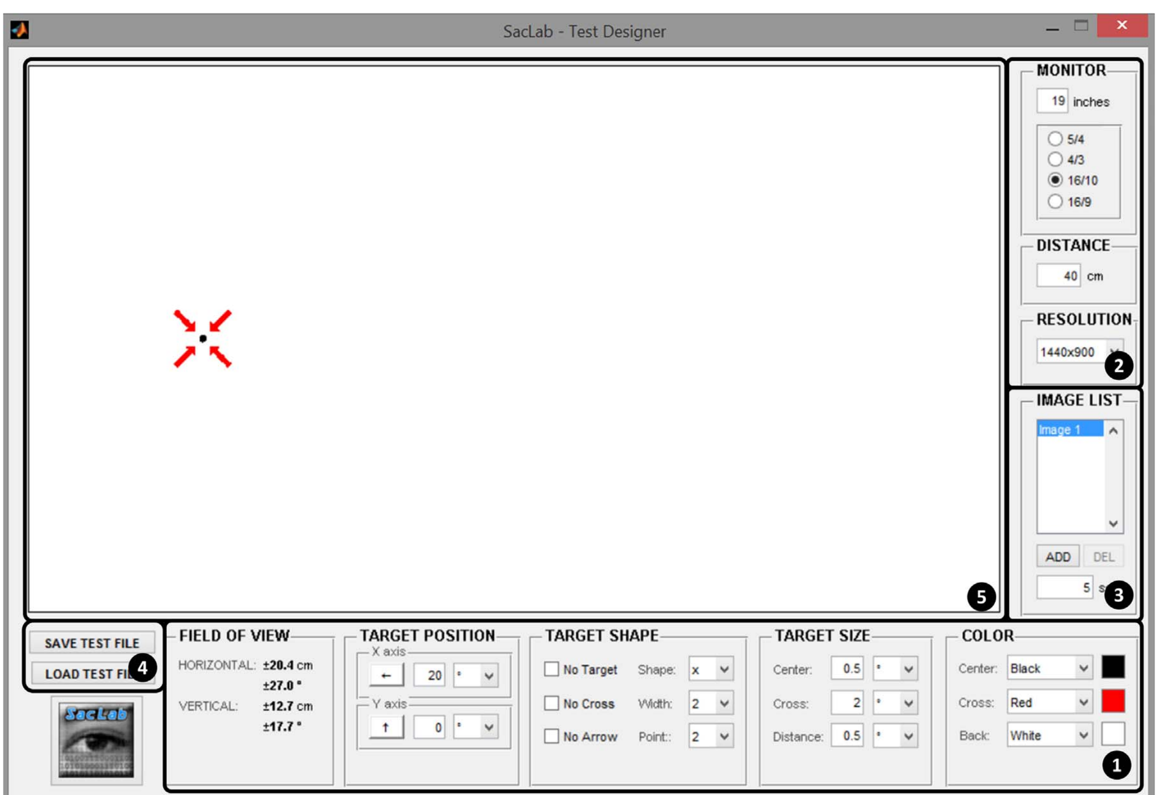

Fig. 3. GUI of TD module: functional blocks. 1)*Stimulus Data*; 2)*Geometry Data*; 3)*Image List*; 4)*File Management*; 5) preview of the created stimulus image.

Table 1
Recordable *Eye Data* available in the ViewPoint ET system.

EYE DATA	DESCRIPTION	COMPONENT 1	COMPONENT 2	UNIT
Gaze point	Position of gaze on the screen expressed as a couple of linear spatial coordinates (X, Y), normalized with respect to the screen size.	X	Y	N/A
Gaze velocity	Velocity at which the Gaze Point moves on the screen, normalized with respect to the maximum measurable speed (screen size·sampling frequency). The two components refer to the same two linear spatial coordinates as the 'Gaze Point' Eye Data.	X	Y	N/A
Gaze Angle	Direction of gaze expressed as a couple of angles, one measured on the horizontal plane (Azimuth angle) and one measured on the vertical plane (Elevation angle).	Azimuth angle	Elevation angle	degrees
Gaze Angular Velocity (GAV)	Angular velocity of gaze, measured on the horizontal plane (Azimuth velocity) and on the vertical plane (Elevation velocity).	Azimuth velocity	Elevation velocity	degrees/s
Fixation time	Duration of a fixation (time period between the end of a saccade and the beginning of the next one)	N/A	N/A	s
Drift	Deviation of gaze point from the initial position of a fixation, expressed as a distance between the current Gaze Point and the first Gaze Point recorded in the fixation.	N/A	N/A	Normalized
Torsion	Rotation of the eye about the gaze axis, calculated with respect to a zero angle measured while the eye is staring at the center of the screen.	N/A	N/A	degrees
Pupil ratio	Ratio between the lengths of the two axes of the pupil, represented as an ellipse; it is used mainly to recognize blinks.	N/A	N/A	Normalized
Pupil size	Pupil area calculated from the length of the two axes of the pupil, represented as an ellipse.	X	Y	Normalized

2.3. Data Analyzer (DA) module

DA module allows to plot and process the recorded Eye Data (saved in the DR output *Data File*) in order to automatically extract a set of parameters of clinical interest for the characterization of the saccadic response.

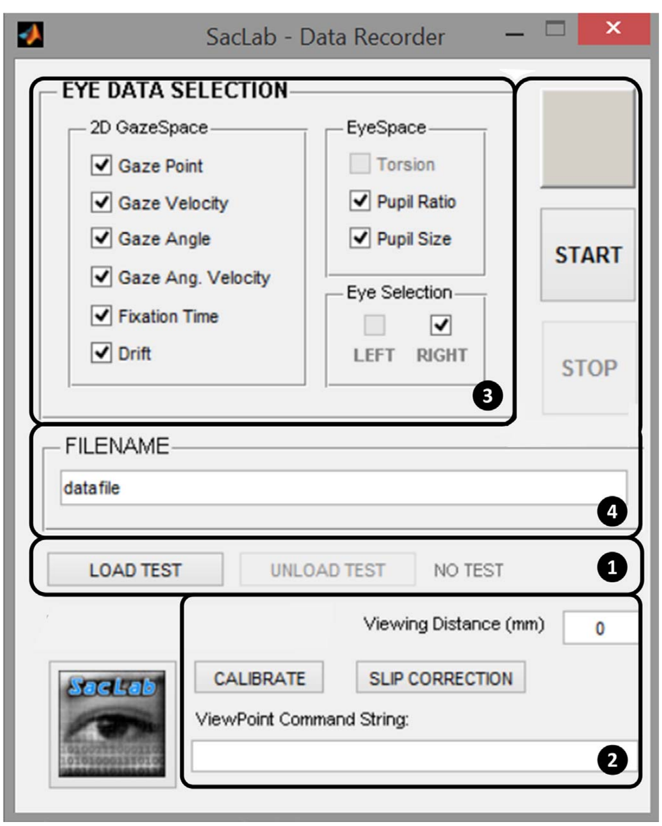

Fig. 4. GUI of DR module: functional blocks. 1)*Test*; 2)*ET communication;*3)*Eye Data Selection*; 4)*Recording*.

The typical workflow in the DA module starts with: 1) loading the recorded Data File; 2) plotting the recorded Eye Data included in the loaded Data File; 3) signal processing of the plotted Eye Data; 4) automatic saccade recognition and saccadic parameters calculation; 5) saving functions.

Plots of the eye movement path can be generated and displayed (*Graphics functions*) in the DA GUI: Eye Data (both components) can be plotted simultaneously for both eyes, using a color-coding (blue and light blue for the right eye, red and orange for the left eye). It is also possible to zoom and scroll each plot through dedicated buttons and sliders provided in the GUI. A MATLAB figure (*Data Plot.fig)* of the plot currently displayed in the DA GUI can be created and saved.

Signal Processing functions are then applied to the plotted Eye Data to clean up the signals from noise and artifact. These functions include: a median filter of selectable order, which is used to remove unwanted spikes in the signals (*Autofilter function*); a function to automatically recognize and remove blinking artifacts using the *Pupil Ratio* Eye Data (*Blink Removal)*; a temporal windowing after each stimulus presentation*,* which is applied to isolate the sections of *Data File* where a saccade is expected (*Stimulus Trim)*; a function to manually select and remove sections of the signal (*Manual Cleaning)*.

The next step is the automatic extraction of saccades from the processed *Data File*. Saccade recognition is performed separately on the two eyes, and saccades are identified as temporal sections during which an eye performs a saccadic movement.

Since saccadic movements are usually composed of a Main (M) saccade and subsequent Corrective (C) saccades [18], we implemented in the DA module a threshold-based saccade recognition algorithm that recognizes the M saccades first and then searches for possible C saccades following them. The algorithm operates on the Gaze Angular Velocity (GAV) array, using four parameters: 1) a threshold for the M saccade (Th_M), 2) a threshold for the C saccades (Th_C), 3) a threshold for the baseline (Th_B) and 4) a search window (*W*). The algorithm starts by searching the sections of the GAV array in which the absolute value is higher than Th_M (M1 section). M1 section is then expanded until the first and last sample have an absolute value lower

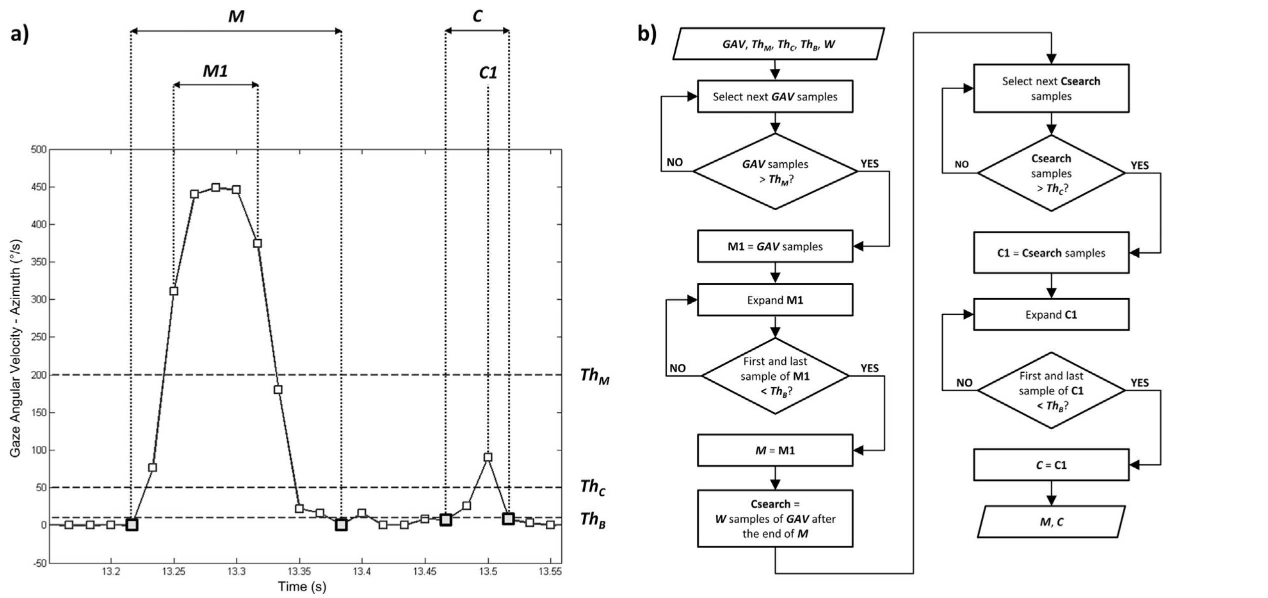

Fig. 5. Graphical example (a) and flow-chart (b) of the implemented saccade recognition algorithm. GAV: Gaze Angular Velocity; Th_M: threshold for Main saccade; Th_C: threshold for Corrective saccades; Th_B: threshold for GAV baseline; W: searching window for corrective saccades. Grey-filled samples represent the start and the end of each recognized M or C saccades.

than Th_B. The obtained expanded section corresponds to the recognized M saccade.

Then, the algorithm starts to search C saccades in the section of the GAV array starting right after the end of M saccade and extending for a length defined by the *W* parameter. The C saccades search is similar to the M saccades search, defining a C1 section based on Th_C value and expanding it until falling below the baseline threshold (Th_B).

For a graphical explanation of the implemented threshold-based saccade recognition algorithm, see Fig. 5.

Settings for the four parameters (Th_M, Th_C, Th_B, *W*) employed by the saccade recognition algorithm can be changed to refine saccade detection and to assure identification of saccades in a wide range of variability, especially to take into account the highly variable nature of C saccades under pathologic conditions [2].

Default values we set for healthy subjects are Th_M,=100 degrees/s, Th_C =20 degrees/s Th_B =5 degrees/s and W =20 samples. Each recognized M saccade is associated to its C saccades, forming the whole *Eye Movement* (EM).

Once all the saccades in a *Data File* have been recognized and the corresponding EM have been defined, the saccadic parameters (Table 2) are calculated *(Saccadic Parameters Calculation functions)* using the *Gaze Angle* and *Gaze Angular Velocity* Eye Data (Fig. 6) and they are saved along with the *Expected Gaze Values* data. The saccadic parameters, that can be referred to M and C saccades or to the whole EM, are collected in a *Saccade Table* and displayed in the GUI of the DA module (Fig. 7).

Finally, the *File Management functions* can be used to save the output file after DA signal processing (*Processed Data File*) and to save both the current plot displayed in the GUI and the extracted saccadic parameters (*Saccade File*). The *Saccade File* is a table containing data about all the saccades recognized and extracted from a processed *Data File*, grouped in EMs. A single saccade is defined by a set of parameters (see Table 2), and is addressed by the following indexes: *Data File* (the name of the file in which the EMs have been recognized); *Left/Right Eye (*the eye to which the movement is referred to); *EM number* (the progressive number of the recognized EM in the *Data File*; *EM section* (section of the EM to which the saccadic parameters refer, i.e. '*Total*' (T) for the whole EM, '*Main*' (M) for the main saccade, '*Corrective N*' (C_N) for the N-*th* corrective saccade). This addressing system allows to analyze single saccadic movements (M or C sections) or a whole EM (T section) composed of the main saccade and corrective saccades. The *Saccade File* can be exported as an Excel sheet (*Saccade Sheet)* for further statistical analysis.

The GUI of DA module is reported in Fig. 7.

By pressing the 'LOAD DATA FILE' button in the bottom-left corner of the GUI (functional block **4**) the recorded *Data File* can be loaded for data processing and saccade recognition. The commands in the top-right corner of the GUI (functional block **3**) are used to select the Eye Data to display in the plot section of the GUI (functional block **5**), in order to check the result of the signal processing functions applied using the commands in the bottom-right corner of the GUI (functional block **1**). Signal processing options include: removal of sections of the *Data File* which are not necessary for saccades recognition ('STIMULUS TRIM' and 'MANUAL CLEANING' panels), removal of blinking artifacts ('BLINK REMOVAL' panel) and of unwanted spikes ('AUTOFILTER' panel).

A *Processed Data File*, which contains the cleaned signals, can be

Table 2
Saccadic parameters calculated by the DA module.

PARAMETER NAME	PARAMETER DESCRIPTION	UNIT
Direction	The direction where the saccade or EM is oriented to, calculated as an angle	degrees
Amplitude	The maximum angle covered by the M/C saccades or by the whole EM.	degrees
Duration	The time elapsed from the beginning to the end of the M/C saccades or EM.	ms
Peak velocity	The maximum gaze angular velocity reached by the M/C saccades or EM.	degrees/s
Latency	The time elapsed between stimulus presentation and the beginning of the saccade (for M saccades or the whole EM); the time elapsed between the end of the previous saccade and the beginning of the following corrective saccade (for the C saccades).	ms
Error	The distance between the final Gaze Angle of M/C saccades or EM and the corresponding value of the Expected Gaze Values array.	degrees

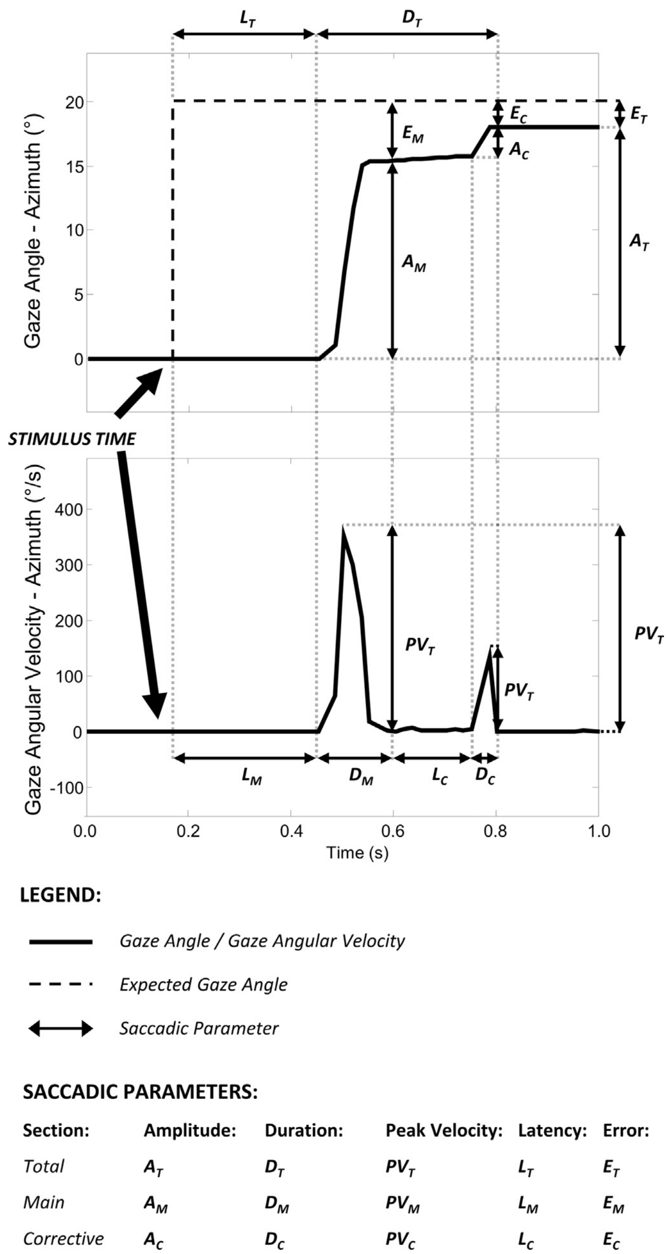

Fig. 6. Example of Gaze Angle (top) and Gaze Angular Velocity (bottom) signals for a horizontal EM and the corresponding saccadic parameters provided by the DA module: these parameters are indexed with reference to the section they refer to (T=Total, M=Main, C=Corrective).

saved by pressing the 'SAVE DATA FILE' button (functional block **4**). By pressing the 'FIND SACCADES' button in the central bottom section in the GUI (functional block **2**), the automatic saccade recognition can be launched, and the saccadic parameters (Table 2) are automatically calculated and displayed in the table displayed in the bottom section of the panel (functional block **2**).

2.4. Saccade Analyzer (SA) module

SA module allows to load the *Saccade Files* created in the DA module and to store them in *Datasets* for providing aggregate data analysis: two saccadic parameters of the *Dataset* can be selected as 'x' and 'y' parameters (*Parameters Selection*) to perform data fitting operations and a scatter (x, y) plot can be displayed. Each point of the plot represents the couple (x, y) of a single saccade in the *Dataset*. *Graphics functions* that include color coding (blue for the right eye, red for the left eye), zooming and axis rescaling functions are implemented for displaying the scatter (x, y) plot referred to a *Dataset*.

SA module implements a set of *Data Fitting functions* to perform data fitting operations on the chosen x, y parameters, fitting the distribution of the 'y' values with a function F(x) of the 'x' values. These fitting functions range from simple linear regression to exponential functions. After data fitting, the residuals (R_i) of each *Dataset* point (x_i, y_i) are calculated as in Eq. (1):

$$R_i=(y_i - F(x_i)) \tag{1}$$

The user can define a threshold to apply to the whole *Dataset*, in order to exclude residuals that fall too far from the fitting function. The residuals are also used to calculate two goodness-of-fit estimators: the Root Mean Square Deviation (RMSD) and the Normalized Root Mean Square Deviation (NRMSD) which normalizes the previous index with respect to the maximum (y_{max}) and minimum (y_{min}) value of the 'y' parameter, calculated as in Eqs. 2, 3:

$$\text{RMSD}=\sqrt{\frac{\sum_{i=1}^{N}(R_i^2)}{N}} \tag{2}$$

$$\text{NRMSD}=\frac{RMSD}{(y_{max} - y_{min})} \tag{3}$$

The fitting function parameters and the resulting RMSD, NRMSD values can be saved in the output *Dataset File,* which collects all saccadic parameters extracted from the aggregate analysis. Additional functions (*Dataset Management functions*) are implemented to select a single *Saccade File* in the Dataset in order to highlight the corresponding saccades in the scatter (x, y) plot, or to exclude one or more *Saccade Files* from the Dataset by applying a set of conditions to the 'x' and 'y' parameters (e.g. setting an allowed range for x, y parameters, or a threshold for the residuals of the fitting function).

The user can also set which eye, which movement direction and which EM section to consider for the x, y parameters selection. *File Management functions* are provided to save the output *Dataset File*, to load a previously created *Dataset File* and to export the current plot as a *Dataset Plot*. The *Dataset File* can also be exported as an Excel sheet *(Dataset Sheet)* and a MATLAB figure of the currently displayed scatter (x, y) plot can be created.

The GUI of SA module is reported in Fig. 8.

By pressing the 'CREATE DATASET FILE' button in the bottom-left corner of the GUI (functional block **5**) a *Dataset File* can be created from the *Saccade Files* processed in the DA module and it is displayed in the list box in the right section of the GUI (functional block **2**). Using the check boxes in the central section of the GUI (functional block **1**) the x, y parameters for the aggregate analysis on the Dataset can be chosen and they are automatically shown in the scatter (x, y) plot (functional block **6**). The scatter (x, y) plot can be managed via the buttons and text boxes in the central top panel of the GUI (functional block **4**).

Data fitting for the scatter (x, y) plot can be set using the commands in the bottom panel of the GUI (functional block **3**): by pressing the 'FIT' button, the selected fitting function is applied to the Dataset, and the result is shown on the scatter (x, y) plot displayed in the GUI. The V and C parameters of the fitting function and the two goodness-of-fit estimators (RMSD and NRMSD) are calculated and displayed in the corresponding text boxes in the panel. Finally, the processed *Dataset File* can be saved by pressing the 'SAVE DATASET FILE' button in the bottom-left corner of the GUI (functional block **5**). The saved file contains all the values of x, y parameters in the Dataset, the V and C parameters of the chosen fitting function and the calculated RMSD and NRMSD values.

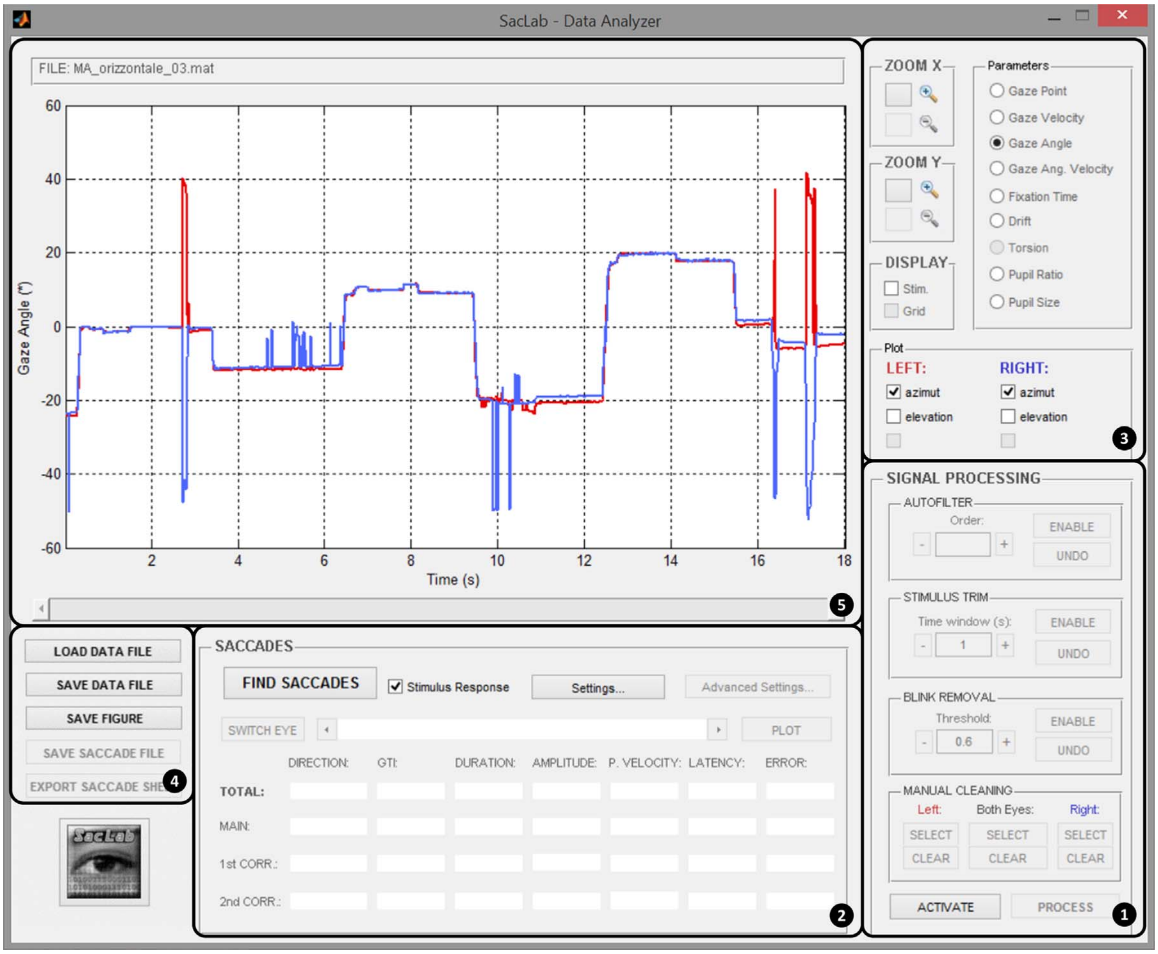

Fig. 7. GUI of DA module: functional blocks. 1)*Signal Processing*; 2)*Saccadic Parameters calculation*; 3)*Graphics*; 4)*File Management*; 5) Plot of *Data File* according to the *Graphics* settings.

3. Results

In this section, we provide a demo application of SacLab toolbox. Demo data were collected from a volunteer with normal binocular vision, who was subjected to an eye tracking test using the ViewPoint ET system (Arrington Research, Scottsdale, AZ, USA) in combination with the new SacLab toolbox. This test was performed with written informed consent from the volunteer and following the ethical standards outlined in the Helsinki Declaration of 1975 and its later amendments. The volunteer sat comfortably on a chair, at 40 cm from the monitor (19”, aspect ratio 5/4), wearing the Eye-frames of the ViewPoint ET system, with her chin rested on a standard headlock for ophthalmologic exams (Fig. 9).

The visual stimuli test was created using the TD module (Fig. 3) and it was designed to elicit horizontal saccades of amplitude of 10, 20, 30 and 40 degrees (Fig. 10).

The created *Test File* was loaded in the DR GUI (Fig. 4). After selection of the Eye Data, the Calibration function was launched and then eye movements recording was started. Data recording was terminated automatically when the visual stimuli test was over. A total of six recordings of the same horizontal test were collected, obtaining six output *Data Files*. Using the DA module, the recorded Eye Data were preliminary cleaned, then the saccades were automatically recognized and their parameters were calculated and saved in six *Saccade Files*.

An example of the *Gaze Angle* and *Gaze Angular Velocity* Eye Data before and after signal processing provided by the DA module is shown in Fig. 11.

SA module was used to create a *Dataset File* from the six *Saccade Files*, and the relationship between the Amplitude (x parameter) and Peak velocity (y parameter) of the Main saccades was analyzed in the Dataset.

From the list of fitting functions in the SA GUI, the ‘plateau’ fitting function was chosen (Eq. (4)):

$$y = V(1 - e^{\frac{-x}{C}}) \tag{4}$$

The result of fitting was displayed in scatter (x, y) plot in the GUI (Fig. 8): the relationship between the Amplitude and Peak velocity parameters for the main horizontal saccades showed that was in accordance with the ‘Saccadic Main Sequence’ reported in the literature for human saccades [19].

A residual threshold of 150 degrees/sec was set in the appropriate text box of the SA GUI to exclude saccades which fell too far from the chosen fitting function. As result, only one point (the pink one in the top-right corner of the scatter (x, y) plot in Fig. 8) was excluded from the *Dataset File* since its residual from the fitting function exceeded the chosen threshold value.

We tested the usability of SacLab toolbox with three ophthalmologists who had no programming experience and who were briefly trained in the use of the toolbox. Then they were asked to perform the previously described demo test for the horizontal saccades analysis, by carrying out all the procedural steps using the SacLab GUIs.

The toolbox gained an enthusiastic feedback from all three ophthalmologists in terms of intuitiveness, ease of use and flexibility. The easy handling of all processing settings through the GUIs, the capabilities of automatic processing and analysis of eye movement

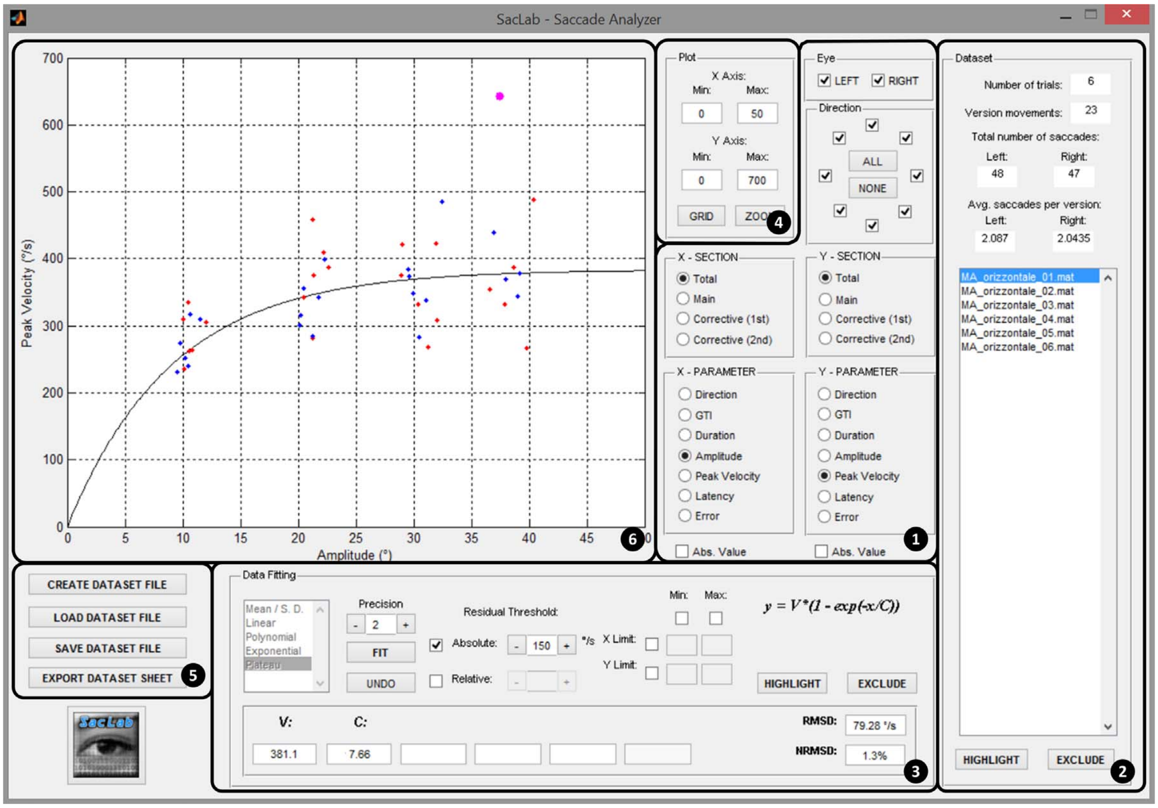

Fig. 8. GUI of SA module: functional blocks. 1)*Parameters Selection*; 2)*Dataset Management*; 3)*Data Fitting*; 4)*Graphics*; 5)*File Management*; 6) Dataset scatter (x, y) plot, according to the *Parameters Selection*, *Graphics* and *Data Fitting* settings.

data, and the visualization features allow the user to shorten the overall test time and provide all tools for handling the complexity of saccade data analysis. The mean time (average over the three users) required for the creation of the visual stimuli test via the TD GUI was 52 ± 21 s. Processing of the recorded Eye Data to clean the signals from noises and blinking artifacts requires that the user opens and checks the results of the automatic processing functions and, in case it is necessary, performs manual cleaning: in our experiment with the three ophthalmologists these operations required a mean time of 46 ± 19 s. The calculation of saccadic parameters from the cleaned *Eye Data* and the aggregate analysis for a *Dataset* of multiple tests were almost immediate operations provided by the software after one-click actions by the user, with results immediately displayed in the GUIs.

Fig. 9. Picture of how the ET system is fixed to the subject.

4. Discussion

In this paper, we have presented SacLab, an intuitive MATLAB toolbox that we have developed to enhance the usability of the ViewPoint ET system in the field of ophthalmology, more specifically for the analysis of saccadic eye movements. SacLab offers a single software package for managing all steps involved in the preparation of eye tracking tests, from the creation of visual stimuli tests to the automated data processing and saccadic analysis at various levels of complexity.

The ViewPoint ET system, as many other commercial low-medium price ET systems, allows only for basic data analysis that is mainly gaze-oriented and does not provide functions to easily create visual stimuli tests or for automatic processing and analysis of the recorded eye movement data. The SacLab toolbox was developed specifically to manage these functions, while maintaining the native ViewPoint ET software for the basic functions like camera setup and calibration.

SacLab resulted an easy-to-use tool, since all the procedural steps

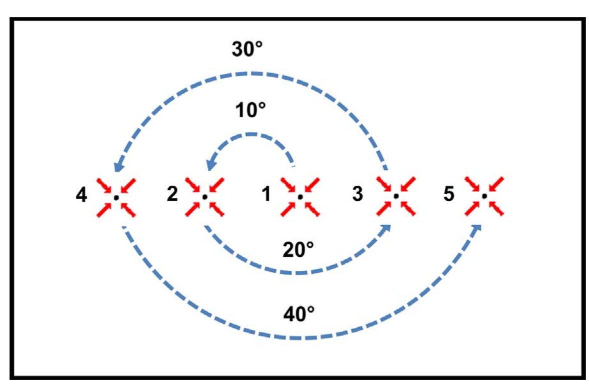

Fig. 10. Example of test created with TD module to elicit horizontal saccades.

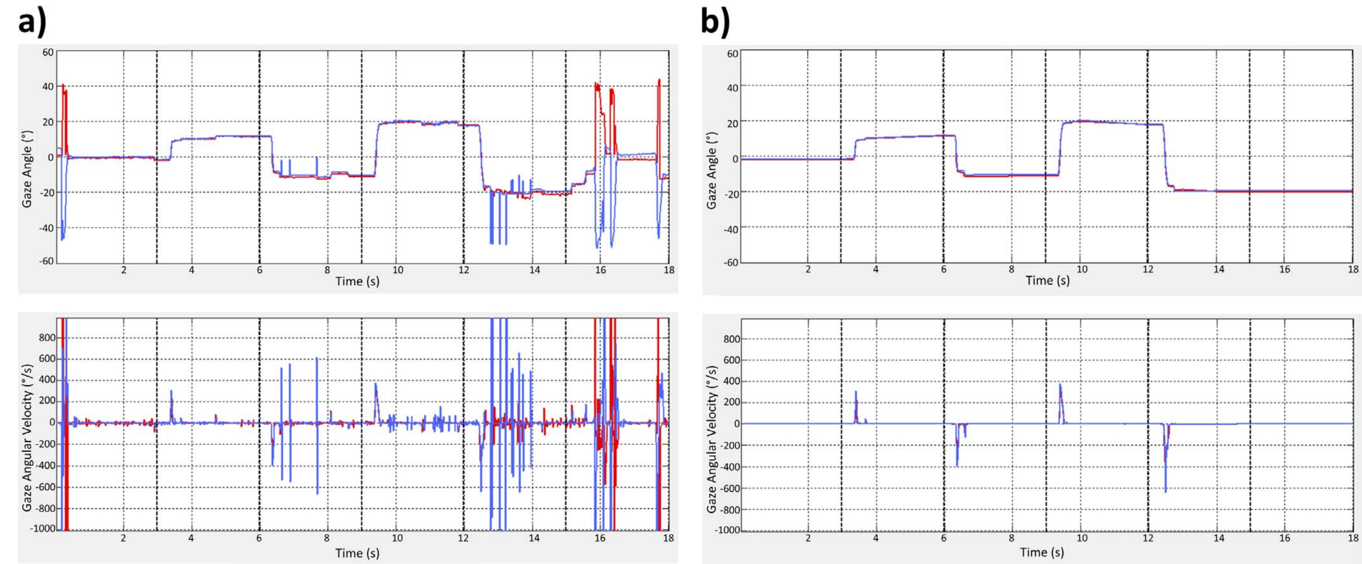

Fig. 11. Example of signal processing provided by DA module. *Data File* plot: *Gaze Angle* (top) and *Gaze Angular Velocity* (bottom) before (a) and after (b) signal processing. The vertical dashed lines represent stimulus time. In the processed signal (b) the start of saccades can be recognized as spikes in the *Gaze Angular Velocity* plot.

were successfully performed by physicians who had no specific programming knowledge, after a brief training on the use of the SacLab GUIs.

Comparing SacLab with other freely available software toolboxes recently developed for the automated analysis of eye movements using ET systems [13–17], one distinctive feature of our toolbox is the possibility to manage the whole process, from the creation of the visual stimuli test to the aggregate analysis of data coming from multiple tests (Table 3). Existing software toolboxes such as GazeAlyze [13], ILAB [14], SmartEye [15] or EALab [16] do not allow the creation of visual stimuli, relying on external interfaces. EALab [16] offers advanced data analysis functions and advanced multivariate analysis, but the automated saccade analysis is limited to only three saccadic parameters (amplitude, duration and peak velocity). PyGaze [17], a toolbox programmed in Python language, gives the possibility to generate visuals stimuli and is capable of recognizing saccadic movements, but it does not allow the automatic extraction of saccadic parameters of clinical interest, that instead are provided by SacLab. In general, all these previously developed toolboxes for ET systems focus mainly on the fields of neurology and psychophysiology [13–17], while SacLab is conceived to be used by ophthalmologists for studying the saccadic eye movements.

Another distinctive feature of SacLab is the analysis of corrective saccades. The user is able to study their direction, peak velocity, latency and precision, and to study the relationship between them and the main saccade. Corrective saccades dysfunctions have been associated to many different diseases [20–22], and we think that the inclusion of advanced functions to study their behavior could be very interesting in future applications; the ophthalmologists who have tested our toolbox share this opinion.

Table 3
Comparing SacLab and other freely available software toolboxes for the analysis of eye movements with ET systems.

FEATURE	GAZEALYZE	ILAB	SMARTEYE	EALAB	PYGAZE	SACLAB
Test design					✓	✓
Data processing	✓	✓	✓	✓	✓	✓
Saccade recognition	✓	✓	✓	✓	✓	✓
Automatic extraction of saccadic parameters	✓	✓		✓		✓
Aggregate analysis of saccadic parameters				✓		✓

We know of some commercially available products [23,24] that offer functions similar to SacLab. The EyeBrain (SuriCog, Paris, FR), for example, is a complete ET system which offers test designing interfaces and advanced functions for the analysis of eye movements, including saccades [23]. The EyeLink ET system (SR Research, Ottawa, Ontario, CAN) comes with an Experiment Builder and a Data Viewer which offer a wide range of possible analysis [24]. However, these toolboxes are proprietary packages designed to be exclusively used with specific commercial ET systems, therefore not freely available and accessible. SacLab is a freely available toolbox and, despite currently it can be interfaced only to the ViewPoint ET system, there is possibility to easily extend it to other ET systems in future software releases.

SacLab is being actively maintained and developed. At present, the functionalities of SacLab are limited to the analysis of saccadic eye movements, however new functionalities, such as the extension of analysis features and the implementation of ad-hoc analyses of other types of eye movements, such as vergence movements, fixations, smooth pursuit and vestibular ocular reflexes, are expected in future versions.

In this paper, we presented a demo test of SacLab application for the analysis of horizontal saccades in a subject with normal oculomotor behavior. The test is reported only to show the SacLab functionalities and potentialities in terms of usability and data analysis, while the interpretation of clinical significance of test results is out of the scope of this preliminary study. However, a fundamental future improvement of SacLab package will be the development of automatic tools to guide the user in the clinical interpretation of the recorded and analyzed data. For this, we are working on collecting data from the literature and from clinical studies we have initiated [25,26] to characterize the saccadic movements in healthy subjects and patients with different pathologies. The idea is to implement in future SacLab versions default Saccade Analyzer functions referred to different pathologies involving saccadic disorders, that automatically make available to the user the most interesting data pairs, plots and model fits for the recorded eye data that may guide the clinical interpretation. As further improvements, after having achieved an accurate classification of the main saccadic disorders as suggested in Thurtell et al. [27], automatic functions could be implemented in the DA module to recognize abnormal saccadic patterns and to provide the user with a list (drop-down menu) of possible pathologies associated with each recognized abnormal saccadic pattern.

In this study, we have presented a pilot application of the SacLab toolbox to a young adult subject. Obviously, the application can be easily extended to pediatric and elderly subjects, by only providing any necessary adjustment to set up the hardware components of the ET system.

In this preliminary test phase, we have interfaced the SacLab software to the commercial ViewPoint EyeTracker manufactured by Arrington Research. To extend the applicability of SacLab to other ET systems, some specific communications functions implemented in the current TD module and DR modules (i.e. the command lines created in the Test File to load the stimulus images in the ViewPoint software and the data acquisition functions in the DR module to retrieve the recorded eye data from the ViewPoint) should be modified and adapted to interface with different ET software. Apart from this, the other SacLab modules (DA and SA modules) are independent from the native ViewPoint ET software, since they operate directly on the acquired eye movement data that any ET system can provide.

5. Conclusions

In this paper, we introduce SacLab, a new intuitive MATLAB toolbox that encompasses in a single package all the main functions needed for a comprehensive and flexible analysis of saccadic eye movements with the ViewPoint EyeTracker System manufactured by Arrington Research. The toolbox can be helpful to expand the use of the ViewPoint ET system among ophthalmologists that currently is limited due to the considerable time required for preparing ET tests and the limited capabilities of automatic processing of the recorded eye data, despite its widespread use in research applications.

Future efforts and developments will be addressed to implement some tools and automatic functions in the SacLab package that may help the users in the clinical interpretation of the recorded eye data.

Conflict of interest statement

None decleared.

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