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Auditory and Visual Stimuli Elicited Saccades

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Auditory and Visual Stimuli Elicited Saccades

Xiu Zhai

B.S., Shenyang University of Technology, 2010

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Submitted in Partial Fulfillment of the
Requirements for the Degree of
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At the
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2013
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Abstract

Many people are at a high risk of suffering a mild traumatic brain injury (MTBI) in current society. The pathology of a concussion is related to the neural network of the brain. It has been indicated that a diagnosis of MTBI can be provided by analyzing fast eye movements. This involves characterizing the neurosensory control of human visual and auditory system.

Saccades are very fast eye movements that allow the eyes to quickly move from one target or image to another. A saccadic eye movement can be triggered by either visual or auditory stimuli. In the work presented in this thesis, saccades induced by visual (V-saccade), auditory (A-saccade) and auditory-visual bisensory (AV-saccade) stimuli that provided in a horizontal plane were recorded and analyzed. Human saccade data was collected using a high speed eye tracking system, and analyzed with a program written in FORTRAN, which computed parameter estimates using the system identification technique for a saccadic eye movement model.

Saccade characteristics were investigated, and the results of saccadic eye movements elicited by the three different stimuli types were compared. Saccade peak velocity increased with increasing saccade amplitude as an exponential shape, while A-saccade showed lower values than V-saccade and AV-saccade. Saccade duration was linearly proportional to saccade amplitude, and it was longer for A-saccade. Saccade latent period was relatively independent of saccade amplitude, but there was a significant reduction in AV-saccade. The neural input for the saccadic model was also estimated. A-saccade exhibited lower agonist pulse magnitude and longer agonist pulse duration in large saccade amplitude. Post saccade phenomena were caused by the post-inhibitory rebound
burst (PIRB) in the antagonist motoneurons. It was concluded that there was a higher incidence of dynamic overshoot in A-saccade, while more in the abducting than the adducting direction saccadic eye movements.

All the results and conclusions will be a solid foundation for the development of the saccadic eye movement neural network model, as well as contribute to the improving and adapting the design for an all-encompassing device that can detect MTBI.
1. Introduction

1.1 Background

In current society, many people are at a high risk of suffering concussions. Mild traumatic brain injuries (MTBI) may happen to players in contact sports such as football and hockey, as well as the active soldiers in the military. To accurately diagnose a patient’s concussion in time for such situations is very important and necessary, since this will lead to a serious long term brain injury and even death.

Dr. John Enderle (Professor in University of Connecticut) has been focusing on the research of fast eye movements for the past thirty years. The current investigation uses visual and auditory stimuli and previously created models of the oculomotor system to begin the early stages of creating a portable device, which can diagnose MTBI by analyzing eye movements. The device is planned for development using visual and auditory stimuli to the eye movement system, which when analyzed, provides inputs to a pattern analysis program and back propagation using a neural network. This will provide a diagnosis for MTBI, and if detected, the location of the injury site can be indicated. To implement this design, the execution of many different types of saccade experiments are carried out, which include goal-oriented saccades, double-step saccades and antisaccades.

1.2 Saccades and Their Characteristics

The visual system is the most important sensory system in the human. The eye movement or oculomotor system helps to acquire, locate and track visual stimuli. It can respond to auditory inputs as well. Saccades are very fast eye movements that allow the
eyes to quickly move from one target or image to another. This type of eye movement is very common and it is used to acquire a target and center the visual image on the fovea.

The eyes can move in three directions (horizontal, vertical and torsional) and saccades happen in a single direction or in any combination. By providing different intended guidance, saccades can be categorized in several ways. In a goal-oriented saccade, a visual or auditory stimulus is given, and a saccade is triggered by the disappearance of a fixation target or the appearance of the peripheral target. In an anti-saccade, eyes move away from the target to the opposite direction. Another type is memory-oriented saccades. There’s no visual or auditory stimuli, eyes move to a remembered point quickly. There are also double-step saccades, where targets will be displayed successively and eyes follow the sequential stimuli.

Saccades are characterized by the properties of saccade amplitude, peak velocity, duration and latent period. Saccade amplitude or saccade size is the angular distance that the eyes travel during a saccadic movement, and is the position difference of the eyes between the beginning of the saccade and the end of the saccade. The eyes can move in both adducting (nasal, toward the nose) and abducting (temporal, toward the temple) directions. In horizontal saccades, we define positive angular displacement as the eyes move to the right direction and negative angular displacement as the eyes move to the left direction. Peak velocity is the maximum angular speed that occurs during a saccadic eye movement. Saccade duration is the time difference from the start to the end of a saccade. Latent period or reaction time is defined as the time between target presentation and the beginning of the saccade. These characteristics for a typical 10 degrees saccade are shown in Figure 1-1.
1.3 Previous Work of Visual and Auditory Saccades

Characteristics of saccadic eye movements induced by visual stimuli have been investigated extensively. A typical experiment uses small light emitting diodes (LEDs) as visual stimuli. They are positioned in the horizontal plane in front of the subjects. Subjects are asked to follow the lit LEDs and a saccade is made when the active LED is switched off and another LED is switched on. Eye movement data can be recorded by using a variety of techniques. The most common method is to use electrooculography (EOG) combined with digital filters.

To investigate saccade dynamics, main sequence diagrams are used to plot the change of saccade parameters versus saccade amplitude (Enderle and Wolfe, 1988; Harwood et al., 1999). In human visual saccades, peak velocity increases with increasing saccade
amplitude with an exponential shape up to about 800 degrees per second when it levels off (Enderle, 1988; Enderle and Zhou, 2010). The relationship fits to the nonlinear equation

\[ v_{\text{max}} = \alpha \left( 1 - e^{-\frac{x}{\beta}} \right) \]  

(1)

where \( v_{\text{max}} \) is the peak velocity, \( x \) is the saccade amplitude, and the constant \( \alpha \) and \( \beta \) are evaluated to minimize the summed error squared between the curve and the data (Enderle, 2010). Duration is linearly proportional to saccade amplitude from 30ms to 100ms, and the linear relationship is more obvious for saccades larger than 7 degrees (Enderle and Zhou, 2010). For saccades less than 7 degrees, saccade duration is approximately constant (Zhou, Chen and Enderle, 2009). Latent period of visual saccades is usually from 100ms to 250ms, it increases slightly with increasing target movements (Engelken, 1987; Zahn et al., 1979). While some other investigators have indicated that the value of latent period appears independent of saccade size, it’s quite clear that no linear relationship can be shown (Enderle and Zhou, 2010).

To explore the saccadic system, the oculomotor plant and saccade generator are the basic elements in any investigation. Enderle and Zhou have presented a 2009 version of state-of-the-art horizontal saccadic eye movement model, which is linear and 3\(^{\text{rd}}\)-order, and controlled by a physiologically based time-optimal neural network. In this model, pulse-slide-step waveforms are described to create the saccades with a post-inhibitory rebound burst. A saccade is initiated by the superior colliculus and terminated by the cerebellum. A total of 25 parameters that describe the oculomotor plant, neural inputs and active-state tensions, are estimated by the system identification technique (Enderle and Zhou, 2010). The model of horizontal saccades involves only one pair of muscles. This is
an agonist-antagonist muscle pair because the muscles’ activity opposes each other. Active-state tension is an internal and immeasurable force inside the muscle and follows the neural input. A pulse stimulates the muscle that is being contracted (agonist), and a pause or a negative pulse to zero is used for the muscle that is being stretched (antagonist), both are followed by a step to maintain the eyeball at its destination, shown in Figure 1-2.

![Diagram of agonist and antagonist muscles](image)

Figure 1-2. Red line: Agonist neural input $N_{ag}$ and antagonist neural input $N_{ant}$.

Blue line: Agonist active-state tension $F_{ag}$ and antagonist active-state tension $F_{ant}$ (Enderle, 2010).
Moreover, a post-inhibitory rebound burst (PIRB) in the antagonist motoneurons causes the post-saccade phenomena (Enderle and Wolfe, 1988; Enderle and Engelken, 1995; Enderle, 2002). Post-saccade phenomena including dynamic overshoots and glissadic overshoots usually happen during human saccades. When the eyes move beyond a target, a quick saccade-like return will occur to make the eyes go back to the target without any delay, this is a dynamic overshoot. A glissade is similar but with a slower return.

The results of visual saccades’ agonist pulse and antagonist pulse parameter estimation using the model discussed above have been presented by Zhou (Zhou et al., 2009). In agreement with the theory for the time-optimal saccade controller proposed by Enderle in 2002, agonist pulse magnitude remains approximately constant for saccades over 7 degrees, while it shows a linear increase for saccades less than 7 degrees. And for saccades of the same amplitude, a great variability is observed in the pulse magnitude estimates. At the same time, the agonist pulse duration increases as a function of saccade amplitude for large saccade degrees, and it is relatively constant in small saccade degrees. Saccades with a dynamic overshoot or glissade have a more notable rebound burst and PIRB occurs with a great randomness. There are more saccades with dynamic overshoot in the abducting than adducting direction, and the PIRB magnitude for dynamic overshoots are usually larger than that for glissades, while the duration of PIRB is approximately 12ms. More discussions about the PIRB and post-saccade phenomena in visual saccades have been provided by Enderle and Zhou in 2010.

On the other hand, much less is known about the saccadic eye movements made in response to auditory stimuli as well as auditory-visual bisensory stimuli. In previous
studies, it is shown that auditory saccades (A-saccade) provide lower peak velocity and longer duration than visual saccades (V-saccade) (LaCroix et al., 1990; Zambarbieri et al., 1982). The reaction time for A-saccade involves multiple complicated processes that the brain has to go through a comparison with a V-saccade. Several researchers have reported that the latent period of A-saccade decreases with increasing target eccentricity (Engelken et al., 1991; Zahn et al., 1978) or at least is greater in small saccade degrees than in larger saccades (LaCroix et al., 1990), and there is a significant reduction of latent period in auditory-visual saccades (AV-saccade) (Engelken and Stevens, 1989). What’s more, A-saccade has lower agonist pulse magnitude than V-saccade, and higher incidence of dynamic overshoot in abducting eye movements happen as well (LaCroix et al., 1990).

1.4 Purpose of the Work

In most of the previous studies, researchers focus on the analysis of single-stimuli induced saccadic eye movements, V-saccade or A-saccade. Thus, the purpose of this study is to investigate V-saccade, A-saccade and AV-saccade at the same time. By using a Hi-Speed eye tracking system as well as the technique of parameter estimation and system identification discussed previously, saccade characteristics including peak velocity, duration, latent period, agonist pulse, antagonist pulse, post saccade phenomena and so on are analyzed and compared.

1.5 Outline of the Thesis

Thus far, the background and previous work have been presented, as well as the purpose of this thesis. Section 2 will introduce the method used in this study, including
the experiment design with software, the data collection with an eye tracking device and the technique used for data analysis. In section 3, experiment results will be shown and the comparison of saccade characteristics will be exhibited. Then, there will be a discussion in section 4, all the related problems that happen in the experiments will be discussed and further investigations of the results will be provided. Finally, a brief conclusion will be given and further work will be illustrated in section 5 and 6.

2. Methods

2.1 Subjects

Four subjects participated in this study, including two males and two females, in age from 20 to 26. None of them disclosed any history of visual, auditory or vestibular disorders, and none was taking any medications that were known for CNS effects. One male and one female had dark color eyes while the other two had light color eyes. All subjects demonstrated normal visual and auditory functions.

2.2 Apparatus and Software

All the tests were performed in an independent, quiet room under normal illumination. The experiments were mainly conducted by a computer workbench using featured software, and data was collected by a high speed eye tracking device (See Figure 2-1).

2.2.1 iSlideCreator for Visual Input

The visual targets were white solid dots on a gray background (Figure 2-2). The images were created by “iSlideCreator” of “Eclipse IDE” using Java. The code is shown
in Figure 2-3. By setting up the frame size in pixels, background color, target color and x, y positions, new images containing the targets could be generated. The visual stimuli were displayed on a computer monitor in front of the subjects.

Figure 2-1. Test environment.

Figure 2-2. Visual stimuli with the target at the center.
Figure 2-3. The Java code for the image creation used in Eclipse.

Nine positions were required for the implementation of visual targets. They were along an arc of a certain radius, at angles of 0°, ±5°, ±10°, ±15° and ±20° from the center, and in the horizontal plane. It was important to determine the exact pixel location for each stimulus in order to create the desired degree eye movements. This required
trigonometric equations involving the dimensions of the display screen and the virtual distance from the subject to the screen. As shown in Figure 2-4, the distance between the screen and the subject was set up as 830mm. We supposed the distance between target and center was $x$ on screen. When wanted to calculate the position of a $10^\circ$ target, it was defined that

$$\tan 10 = \frac{x}{830\text{mm}}$$  \hspace{1cm} (2)

All the parameters are shown in Table 2-1.

![Figure 2-4. The geometry for target displacement.](image)

2.2.2 Adobe® Audition and H3D for Auditory Input

The auditory targets were sounds that generated and modified by Adobe Audition CS5.5 and H3D Binaural Spatializer. The original files were 32-bit stereo audio files with the sample rate of 4.41kHz. The duration of the audio waveform was 3000-5000ms with an average loudness around 30dB (Figure 2-5). The frequency of the sound was 1kHz.
In order to coordinate the sound sources with visual stimuli, three dimensional positional audio was used for auditory tests. The sounds were heard as if in the 3D space, and this was implemented by using H3D Binaural Spatializer plug-in, which was created by Longcat Audio Technologies. Binaural audio rendering consists in recreating the corresponding signals in each ear to a real-life acoustic field. In order to build the two
signals sent to each ear, several parameters are taken into account for the binaural techniques, such as the interaural time delay (ITD) and the interaural intensity difference. The interaural time delay is the time difference between when one ear hears the sound compared to when the opposite ear hears the same sound. The interaural intensity difference is the difference in sound intensity heard by both ears from the same sound. These processes are shown in Figure 2-6. The parameter varies in the source direction relatively to the listener, and head related transfer function (HRTF) can be made.

![Figure 2-6. Interaural time delay and interaural intensity difference.](image)

The H3D plug-in was applied to the host of Adobe Audition and was inserted on every track containing sound that needed to be spatialized. It allowed visualizing and editing the position of the sound by setting up the parameters, including the X, Y, Z coordinates of the source, the size of the virtual room, the stereo width and so on (shown in Figure 2-7). A 3D view is shown in Figure 2-8, it is used to monitor and author the spatialization of the sounds in the project. The parameter set up of the H3D is shown in Table 2-2. The sound source locations were exactly the same with the visual stimuli locations. A modified $10^6$ target waveform is shown in Figure 2-9.
Figure 2-7. Longcat H3D plug-in window, parameters are for a 10º target.

Figure 2-8. Longcat H3D plug-in 3D visual interface for a 10º target.
<table>
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<th>-20</th>
<th>-15</th>
<th>-10</th>
<th>-5</th>
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<th>5</th>
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<td>Left &amp; Right (m)</td>
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<td>-0.222</td>
<td>-0.146</td>
<td>-0.073</td>
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<td>0.146</td>
<td>0.222</td>
<td>0.302</td>
</tr>
<tr>
<td>Back &amp; Front (m)</td>
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<td>0.83</td>
<td>0.83</td>
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</tr>
<tr>
<td>Down &amp; up (m)</td>
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<td>0</td>
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<table>
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<th>Damp</th>
<th>Stereo Width</th>
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</thead>
<tbody>
<tr>
<td>0.00%</td>
<td>50.00%</td>
<td>0.00%</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2-2. H3D parameters for auditory targets, in reference to the position of the subject.

Figure 2-9. The waveform of a 10° sound source shown in Adobe Audition.

Figure 2-10. Bose QuietComfort® 2 Acoustic Noise Cancelling® headphone.
All the auditory stimuli were heard by a Bose QuietComfort® 2 Acoustic Noise Cancelling® headphone (shown in Figure 2-10) during the tests. This stereo headphone could electronically identify and reduce the unwanted noise around the subjects, as well as implement the acquisition of the 3D sound sources.

### 2.2.3 SMI Experiment Center™ for Stimulus Presentation

The visual target motion was generated by changing the images that displayed on the screen, so the position of the white dot could be moved. This was implemented by using the software Experiment Center of SensoMotoric Instruments (Figure 2-11), which was designed particularly for usability testing, marketing research and psychological, physiological, neurological experiments.

![Figure 2-11. SMI Experiment Center™ workbench.](image)
As shown in Figure 2-12, we chose the images that created previously as the visual stimuli. One stimulus contained one image, and the operator could set the properties of each stimulus individually according to the experiment objective. In our experiments, we mainly set up the duration for each image presentation.

![Figure 2-12. The list of stimuli.](image)

The audio files were inserted as audio playback in the corresponding stimulus images as shown in Figure 2-13. The corresponding visual and auditory stimuli were presented together and triggered synchronously. If auditory stimulus needed to be presented alone, a blank image without any dot was used.

![Figure 2-13. Audio insertion.](image)
2.2.4 SMI iView X™ for Data Collection

Eye movements were recorded by using the iView X™ system, which was also designed by SMI for eye tracking study. The main eye tracking method used in this system was a dark pupil eye tracking system, which applied infrared (IR) illumination and computer-based image processing. By detecting the pupil, calculating the center and eliminating artifacts, images of the eye were analyzed in real-time. Once a calibration was performed, the pupil location was translated into gaze data.

The iView X™ system consisted of the following components.

First, an eye tracking camera system was needed. The iView Hi-Speed system was used in our work. This was an easy-to-use, hyper-accurate, monocular, high speed, desktop eye tracker, of which the sample rate was 1250Hz. The camera and the IR illumination resided inside a stand-alone Tracking Column with an integrated ergonomic chin/forehead rest, as shown in Figure 2-14. The subject’s head was stabilized by the chin rest and forehead rest in front of the camera. Thus, lacking the need for time-consuming camera adjustment, it was easy to operate and it was comfortable for the test person to stay accurate even for a long time recording.

Then, the iView X™ workstation was provided, which contained the eye tracking computer system that ran the iView X™ software, as well as the Hi-Speed system that allowed the system to capture eye movements. The iView X™ work station controlled the camera equipment, at the same time, processed all eye and scene video signals from the experiment, shown in Figure 2-15. In the eye image window, the white cross-hair marked the center of the pupil, the black cross-hair marked the corneal reflex. In most applications, one or several corneal reflexes would be tracked by the iView X™ system.
in order to compensate for changes in position of the camera relative to the head. Thus in the iView Hi-Speed system we used, small movements of the head were compensated.

Moreover, the SMI Experiment Center™ that we introduced previously could be run synchronously with iView X™. Stimulus events presented with the Experiment Center™ could be synchronized with data collection by the iView X™ workstation.

The result of the measurement was a binary iView Data File (.idf file) that was recorded and stored automatically. This system output was used as a basis for further analysis. The IDF file could be loaded into the IDF Converter, which could exports various kinds of data, such as pupil size and position, gaze position, detected saccades and fixations, etc. The output format we chose was plain text, and the exported items were shown in Figure 2-16. Further data processing and analysis methods will be discussed in Section 2.5.

Figure 2-14. iView X Hi-Speed system.
Figure 2-15. iView X™ work window with eye and scene video.

Figure 2-16. IDF Converter export configuration.
2.3 Experiment Design

2.3.1 Stimulus Condition

Subjects were tested under three tracking conditions. Different kinds of stimuli targets were presented in each condition.

In V-saccade, only visual stimuli were presented. Subjects responded to each target movement. A saccade was made when the dot disappeared at one position and appeared at another position.

In AV-saccade, visual stimulus and auditory stimulus were displayed together and moved synchronously. Since the onset of the visual target presentation and the audio sound were at the same time and came from a same source position, subjects responded to both stimuli.

In A-saccade, when the target was at the center, which was the fixation point, both visual and auditory stimuli were exhibited. The auditory stimulus was displayed alone at a peripheral position without any visual cue, and the stimulus screen was blank at this time. Subjects made a response after they heard the sound onset and would locate the position of the source as soon as possible.

2.3.2 Stimulus Sequence

In all of the three experiments (V-saccade, AV-saccade and A-saccade), the targets were presented in a same sequence.

There were four sections in one experiment, which were 5 degrees section, 10 degrees section, 15 degree section and 20 degree section. In each section, the target presentation started at the center position, and then moved to a peripheral position, a saccade
happened during this time. Then, the fixation point appeared at the center again, followed by another movement to the right or left direction, etc. If we neglected the fast eye movements that happened when the target moved back from the peripheral position to the center fixation, and only counted the saccades from center to the peripheral position, there were a total of 16 saccades in each section of a degree, thus 64 saccades in one experiment. It was known that the positive saccades could be defined as the right direction, and the negative saccades were in the left direction. Thus, the sequence of the 16 saccades in a single section was described as / + - + + / - + - - / - + + - / + - - + /. The four sections of the experiment were operated to start manually after the first center target was presented and the subject showed that he/she was ready. Between each of the two sections, a short break was provided that the subjects could relax and blink during this period without changing the head and sitting position, usually within 10 seconds. The duration of any other single stimulus presentation was randomly from 3000ms to 5000ms.

The sequence and the duration of the stimuli for V-saccade, AV-saccade and A-saccade experiments are shown in Figure 2-17.
Figure 2-17 (a). Stimulus sequence and duration in V-saccade and AV-saccade.

Left column: 5° and 10° sections. Right column: 15° and 20°.
Figure 2-17 (b). Stimulus sequence and duration in A-saccade.

Left column: $5^\circ$ and $10^\circ$ sections. Right column: $15^\circ$ and $20^\circ$. 
2.4 Testing Procedure

2.4.1 General Testing Procedure

One subject was required to take 3 experiments successively in a single session, in the sequence of V-saccade, AV-saccade and finally A-saccade. This was because in a same day and a same period of time, the performance of a subject as well as the device could keep relatively constant. Thus, the result’s comparability was more reasonable. Since it was easier for a subject to locate the visual targets, V-saccade was taken first, followed by adding the corresponding sound source which was AV-saccade that with the bisensory stimuli. A-saccade was taken at last. With the experience of the previous experiments, subjects were more confident to respond to and locate the auditory stimulus without any visual cues.

2.4.2 Eye Camera Setup

Each time for the testing, the parameters of the Hi-Speed eye camera needed to be adjusted at the beginning, as well as after the break that between different experiments if the subject moved his head, or another subject was alternated to collect data.

The subject was asked to sit in front of the tracking column with the forehead and chin properly placed on the rest comfortably and stably, as shown in Figure 2-14. Adjust the tilt of the mirror and the horizontal position of the camera until the left eye was centered in the eye image control window, as shown in Figure 2-15. The “Focus” was also adjusted until the corneal reflection was as small as possible, and this could assure optimal focus on the eyeball. When the subject was asked to look at the center of the monitor, the “Pupil Threshold” and “CR Threshold” (Figure 2-18) were adjusted until a
white cross-hair was centered on the pupil, and a black cross-hair on the corneal reflex (CR). “Auto Adjust” could be used for the automatic adjustment of the pupil threshold and the image balancing by the system. If the image seemed to be blurred, too dark or too bright, “Contrast” and “Brightness” could be adjusted in “Image Adjust” (Figure 2-19). The proper values of these two parameters were always different between dark color pupil subjects and light color pupil subjects.

To ensure the quality of the data, all the parameters of the camera need to be adjusted carefully and patiently. Setup was complete only if the two cross-hairs kept on following the pupil and the CR when the subject looked at the corners and any other positions of the screen. The circle around the pupil should be stable without any flutter.

Advanced adjustment might be applied in some situations, including “pupil area”, “pupil density”, “reflex pupil distance”, and so on.

![Image](image.png)

**Figure 2-18. Pupil and CR adjustment for the Hi-Speed camera.**

![Image](image.png)

**Figure 2-19. Brightness and Contrast adjustment for the Hi-Speed camera.**
2.4.3 Calibration before Data Collection

After the operation for camera setup, the experiment could be run in Experiment Center. A calibration was performed before the final data collection. Calibration was called the process, in which the iView X system established a relationship between the position of the eye in the camera view and a gaze point in space, the so-called point of regard (POR), as well as a plane in space where eye movements were rendered (iView X™ 2 Manual, 2011). Such a reference measurement was run before every experiment, since the relationship discussed above depended on the overall system setup and varied between subjects.

The system would show a “Validation Quality” window after the calibration, including the average deviation of x, y positions. It was better to get both the x, y deviation smaller than 1º, and no obvious deviation on any of the four points. As shown in Figure 2-20 (a), the deviation for the left upper point is large, it is recommended to repeat the calibration or readjust the camera setup. Figure 2-20 (b) shows an acceptable result for the calibration, the experiment can be continued for the data collection.

After the calibration, the subject should keep his head position during the experiment. The data was saved automatically by the iView X system after the experiment.
Figure 2-20 (a). Obvious deviation on the left upper point.

Figure 2-20 (b). Acceptable deviation result for the calibration.
2.5 Data Processing and Analysis

Figure 2-21 displays a flow chart of the entire data processing procedure.
2.5.1 iView Data File and ASCII Readable Text

As previously mentioned in Section 2.2.4, a binary iView Data File (.idf file), which was used as a basis for further analysis, was generated and saved automatically by the system. This file contained the information of pupil and gaze data, which was needed to extract saccades, fixations and so on.

The IDF Converter was then used, converting the IDF to ASCII readable text. The output file consisted of two parts, which were the Header and the Data Section. This file was named as “*_data Samples.txt”.

The Header was subdivided into several groups with a title in squared brackets. Each group provided the information that related either to the system setup or the calibration result. An example of the Header file is shown below:

```plaintext
## [iView]
## Converted from: Z:\Goal Oriented Saccades\Horizontal Saccades\Hi-Speed\Zhai_12-18-2012-eye_data.idf
## Date: 18.12.2012 17:04:24
## Version: IDF Converter 3.0.16
## IDF Version: 9
## Sample Rate: 1250
## Separator Type: Msg
## Trial Count: 1
## Uses Plane File: False
## Number of Samples: 672623
## Reversed: none

## [Run]
## Subject: Zhai_12-18-2012_V
## Description:
```
## [Calibration]

**Calibration Type:** 13-point  
**Calibration Area:** 2560 1600  
**Calibration Point 0:** Position(1280;800)  
**Calibration Point 1:** Position(128;80)  
**Calibration Point 2:** Position(2432;80)  
**Calibration Point 3:** Position(128;1520)  
**Calibration Point 4:** Position(2432;1520)  
**Calibration Point 5:** Position(128;800)  
**Calibration Point 6:** Position(1280;80)  
**Calibration Point 7:** Position(2432;800)  
**Calibration Point 8:** Position(1280;1520)  
**Calibration Point 9:** Position(704;440)  
**Calibration Point 10:** Position(1856;440)  
**Calibration Point 11:** Position(704;1160)  
**Calibration Point 12:** Position(1856;1160)

## [Geometry]

**Stimulus Dimension [mm]:** 640 400  
**Head Distance [mm]:** 830

## [Hardware Setup]

**System ID:** jenderle-3  
**Operating System:** 5.1  
**iView X Version:** 2.7.13

## [Filter Settings]

**Heuristic:** False  
**Heuristic Stage:** 0  
**Bilateral:** True  
**Gaze Cursor Filter:** True  
**Saccade Length [px]:** 80  
**Filter Depth [ms]:** 20  
**Format:** LEFT, RAW, DIAMETER, CR, POR, QUALITY, MSG, FRAMECOUNTER
In Data Section, there were an equal number of tab-delimited columns. The number and type of the columns depended on the export settings. In our system, we exported the following parameters (iView X™ 2 Manual, 2011):

Time: time counter in microseconds

Type: indicates whether the row describes a sample (SMP), or a message (MSG) such as the name of the stimulus file.

Trial: trail number

L Raw X [px]: raw data position of the left eye, in X direction and in pixels

L Raw Y [px]: raw data position of the left eye, in Y direction and in pixels

L Dia X [px]: pupil diameter of the left eye, in X direction and in pixels

L Dia Y [px]: pupil diameter of the left eye, in Y direction and in pixels

L CR1 X [px]: corneal reflex position of the left eye, in X direction and in pixels

L CR1 Y [px]: corneal reflex position of the left eye, in Y direction and in pixels

L POR X [px]: point of regard (gaze data) of the left eye, in X direction and in pixels

L POR Y [px]: point of regard (gaze data) of the left eye, in Y direction and in pixels

Timing: indicates timing violation, if delayed, the value is 1, else 0

Latency: latency in microseconds

Pupil Confidence: indicates validity of pupil diameter values

Frame: frame counter

Aux1: auxiliary data

A selected section of the data is shown below in Table 2-3:
<table>
<thead>
<tr>
<th>Time (s)</th>
<th>SMP</th>
<th>Temperature</th>
<th>Humidity</th>
<th>Pressure</th>
<th>VD</th>
<th>VMA</th>
<th>VD - VMA</th>
<th>VD - VMA</th>
<th>VD - VMA</th>
<th>VD - VMA</th>
<th>VD - VMA</th>
</tr>
</thead>
<tbody>
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<td>121.06</td>
<td>101.85</td>
<td>47.00</td>
<td>46.00</td>
<td>105.06</td>
<td>118.75</td>
<td>0.00</td>
<td>0.00</td>
<td>0</td>
<td>1041</td>
</tr>
<tr>
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<td>SMP</td>
<td>121.10</td>
<td>101.83</td>
<td>47.00</td>
<td>46.00</td>
<td>105.07</td>
<td>118.76</td>
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<td>0.00</td>
<td>0</td>
<td>968</td>
</tr>
<tr>
<td>321698003377</td>
<td>SMP</td>
<td>121.13</td>
<td>101.89</td>
<td>47.00</td>
<td>46.00</td>
<td>105.07</td>
<td>118.76</td>
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<td>0.00</td>
<td>0</td>
<td>964</td>
</tr>
<tr>
<td>321698004163</td>
<td>SMP</td>
<td>121.08</td>
<td>101.83</td>
<td>47.00</td>
<td>46.00</td>
<td>105.08</td>
<td>118.75</td>
<td>0.00</td>
<td>0.00</td>
<td>0</td>
<td>1058</td>
</tr>
<tr>
<td>321729588184</td>
<td>MSG</td>
<td>1</td>
<td>Message: 5 degrees.jpg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>321729588670</td>
<td>SMP</td>
<td>122.08</td>
<td>87.85</td>
<td>43.00</td>
<td>40.00</td>
<td>108.05</td>
<td>107.48</td>
<td>1259.37</td>
<td>820.18</td>
<td>0</td>
<td>1064</td>
</tr>
<tr>
<td>321729589454</td>
<td>SMP</td>
<td>122.03</td>
<td>87.83</td>
<td>42.00</td>
<td>41.00</td>
<td>108.04</td>
<td>107.50</td>
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<td>819.93</td>
<td>0</td>
<td>2354</td>
</tr>
<tr>
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<td>87.89</td>
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<td>40.00</td>
<td>108.05</td>
<td>107.49</td>
<td>1259.02</td>
<td>821.32</td>
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<td>1762</td>
</tr>
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<td>87.88</td>
<td>43.00</td>
<td>41.00</td>
<td>108.04</td>
<td>107.51</td>
<td>1258.28</td>
<td>821.59</td>
<td>0</td>
<td>833</td>
</tr>
<tr>
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<td>122.04</td>
<td>87.93</td>
<td>43.00</td>
<td>41.00</td>
<td>108.03</td>
<td>107.51</td>
<td>1258.21</td>
<td>823.17</td>
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<td>835</td>
</tr>
<tr>
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<td>SMP</td>
<td>122.08</td>
<td>87.96</td>
<td>43.00</td>
<td>41.00</td>
<td>108.05</td>
<td>107.52</td>
<td>1258.74</td>
<td>824.77</td>
<td>0</td>
<td>833</td>
</tr>
<tr>
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<td>122.04</td>
<td>87.96</td>
<td>43.00</td>
<td>41.00</td>
<td>108.03</td>
<td>107.54</td>
<td>1258.70</td>
<td>825.09</td>
<td>0</td>
<td>855</td>
</tr>
<tr>
<td>321729594295</td>
<td>SMP</td>
<td>122.07</td>
<td>88.00</td>
<td>42.00</td>
<td>41.00</td>
<td>108.02</td>
<td>107.53</td>
<td>1259.45</td>
<td>826.37</td>
<td>0</td>
<td>859</td>
</tr>
<tr>
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<td>SMP</td>
<td>122.02</td>
<td>88.01</td>
<td>42.00</td>
<td>41.00</td>
<td>108.03</td>
<td>107.58</td>
<td>1258.87</td>
<td>826.22</td>
<td>0</td>
<td>980</td>
</tr>
<tr>
<td>321729595743</td>
<td>SMP</td>
<td>122.09</td>
<td>88.04</td>
<td>43.00</td>
<td>40.00</td>
<td>108.04</td>
<td>107.57</td>
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<td>827.04</td>
<td>0</td>
<td>995</td>
</tr>
<tr>
<td>321729596531</td>
<td>SMP</td>
<td>122.06</td>
<td>88.04</td>
<td>43.00</td>
<td>40.00</td>
<td>108.04</td>
<td>107.58</td>
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<td>827.48</td>
<td>0</td>
<td>973</td>
</tr>
<tr>
<td>321729597316</td>
<td>SMP</td>
<td>122.07</td>
<td>88.03</td>
<td>42.00</td>
<td>41.00</td>
<td>108.06</td>
<td>107.58</td>
<td>1259.07</td>
<td>827.38</td>
<td>0</td>
<td>975</td>
</tr>
</tbody>
</table>

Table 2-3. A selection of the ASCII file’s Data Section.
2.5.2 LabVIEW “Write to Text” Program

Since the data was finally analyzed in a DATANAL program that was written in FORTRAN language, a LabVIEW program was used ahead in order to implement the data processing. The main idea was to pick out the proper data that we needed from the original ASCII text file, transfer the gaze pixel data into degree values, and create a new set of text files that could properly be analyzed in FORTRAN.

Figure 2-22 shows the front panel of the LabVIEW “Write to Text” program. A “*_data Samples.txt” file that we mentioned previously will be chosen to be converted. The corresponding experiment type needs to be selected since the program involves the conversion code for all the different types of experiments. The LabVIEW program will automatically save the new files in the same directory as the input file that is chosen.

![LabVIEW “Write to Text” front panel.](image)

The block diagram of the LabVIEW “Write to Text” program is shown in Figure 2-23. An original text data file will be selected first. Since the only data we want is in the L POR X [px] and L POR Y [px] columns, which is the X and Y directions’ gaze data of the left eye accounted in pixel, all the other unnecessary rows and columns will be deleted. According to the previously known information of the saccade latency and
duration, we only select the first 500ms’s data after each stimulus change, and a normal saccade can be completely shown in this period. Thus, depends on the 1250Hz sample rate of the camera, the first 625 pairs of data after each stimulus presentation at the peripheral position are taken for further analysis.

The original data will be divided into four parts according to the four sections of the experiment, which are 5 degrees section, 10 degrees section, 15 degrees section and 20 degrees section. In each part, 16 sets of eye movement data are separately outputted. If \( x = L\text{POR}X\;[\text{px}] \) and \( y = L\text{POR}Y\;[\text{px}] \), according to the geometry of the stimulus screen and the subject’s position, as well as the relationship between the screen dimension and the pixels, the X and Y raw pixel data can be converted to degree values by the following equations,

\[
X\;\text{Direction\;Degree} = \tan^{-1}\left( x - 1280 \times \frac{0.25}{830} \times \frac{180}{3.14} \right) \quad (3)
\]

\[
Y\;\text{Direction\;Degree} = \tan^{-1}\left( y - 800 \times \frac{0.25}{830} \times \frac{180}{3.14} \right) \quad (4)
\]

After the process above, the new degree values of the X and Y data will be put back into a two column array. The corresponding saccade degree values including the sign are inserted into a new row at the start of each stimulus change. Necessary initializations and spacing are also added in order to satisfy the format requirements of the FORTRAN program. Four text files named “*.fiv”, “*.ten”, “*.fif” and “*.twe” will be saved automatically in the same directory as the original file which is chosen to be converted.
Figure 2-23 (a). LabVIEW “Write to Text” block diagram Part I.
Figure 2-23 (b). LabVIEW “Write to Text” block diagram Part II.
2.5.3 Excel Plot for the Data

The converted data that saved in the text files was first plotted in Microsoft® Excel. The reasons of doing this were to check the quality of the data, to give a prediction of which saccades could be successfully analyzed in FORTRAN program and which could not. Here, we only picked out the X direction degree values for each saccade to plot, since we were doing horizontal saccades experiments, and the saccadic eye movement model we used later for data analysis was also designed for horizontal saccades. The Y direction’s position was supposed to be stable.

Figure 2-24 shows the plot of a 5 degree saccade. It contains the degree placement of 625 data, which is the horizontal position recording of the eye movement in the first 500ms after the peripheral target presentation.

Figure 2-24. Excel plot of a 5 degree saccade.
2.5.4 FORTRAN Program for Data Analysis

The main data analysis method used in this project was the DATANAL program, which was written in FORTRAN language by Zhou in 2007. It was used to compute parameter estimates for a model of 1d saccadic eye movements.

The model used in DATANAL program had been presented by Zhou et al. in 2009 and a detailed expansion had been provided by Enderle (2010) in his book Models of Horizontal Eye Movements, Part II. This model was linear, 3\textsuperscript{rd}-order and used for the analysis of horizontal saccadic eye movements. It consisted of a linear ocularmotor plant, which included the eyeball as well as two extraocular muscles, and a time-optimal saccadic controller based on physiological considerations, the neural inputs were described by pulse-slide-step waveforms with a post inhibitory rebound burst (Zhou et al., 2009). All the parameters and initial conditions were estimated using the system identification technique from physiological data.

Figure 2-25 shows the flow chart of DATANAL FORTRAN program. Table 2-4 lists the files that compose the program, and Table 2-5 lists the subroutines.
Figure 2-25. DATANAL FORTRAN program flow chart.
<table>
<thead>
<tr>
<th>File Name</th>
<th>Description</th>
<th>In Which File</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATANAL1.F90</td>
<td>Main program, subroutine for initial estimation of model parameters</td>
<td></td>
</tr>
<tr>
<td>DATANAL2.F90</td>
<td>Interface of estimation subroutine</td>
<td></td>
</tr>
<tr>
<td>DATANAL3.F90</td>
<td>Estimation subroutine (conjugate gradient search, cost function, etc.)</td>
<td></td>
</tr>
<tr>
<td>DATANAL4.F90</td>
<td>Determination of final solutions, other functions</td>
<td></td>
</tr>
<tr>
<td>Input.F90</td>
<td>Data input</td>
<td></td>
</tr>
<tr>
<td>Incl.F90</td>
<td>Definition of input format (human data), program constants</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-4. DATANAL program files.

<table>
<thead>
<tr>
<th>Subroutine Name</th>
<th>Description</th>
<th>In Which File</th>
</tr>
</thead>
<tbody>
<tr>
<td>(main program)</td>
<td>Main program (entrance) Read data, run each case and prints solutions</td>
<td>DATANAL1.F90</td>
</tr>
<tr>
<td></td>
<td>Call InputData, InitGuess, PAREST and SOLUT</td>
<td></td>
</tr>
<tr>
<td>InitGuess</td>
<td>Initial estimates of model parameters</td>
<td>DATANAL1.F90</td>
</tr>
<tr>
<td>PAREST</td>
<td>Interface of estimation subroutine</td>
<td>DATANAL2.F90</td>
</tr>
<tr>
<td></td>
<td>Call CONGRD</td>
<td></td>
</tr>
<tr>
<td>CONGRD</td>
<td>Perform a conjugate gradient search function minimization</td>
<td>DATANAL3.F90</td>
</tr>
<tr>
<td></td>
<td>Call GRAD and COSTFG</td>
<td></td>
</tr>
<tr>
<td>GRAD</td>
<td>Computer numerical gradient of cost function</td>
<td>DATANAL3.F90</td>
</tr>
<tr>
<td>COSTFG</td>
<td>Cost function</td>
<td>DATANAL3.F90</td>
</tr>
<tr>
<td></td>
<td>Call constraint subroutines such as Constrain,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Constrain1, ConstrainLU</td>
<td></td>
</tr>
<tr>
<td>Constrain</td>
<td>Add constraint to the cost function</td>
<td>DATANAL3.F90</td>
</tr>
<tr>
<td>Constrain1</td>
<td></td>
<td>DATANAL3.F90</td>
</tr>
<tr>
<td>ConstrainLU</td>
<td></td>
<td>DATANAL3.F90</td>
</tr>
<tr>
<td>SOLUT</td>
<td>Determine final solution</td>
<td>DATANAL4.F90</td>
</tr>
<tr>
<td></td>
<td>Call COSTFG, outmat, outsignal and outanalysis</td>
<td></td>
</tr>
<tr>
<td>outmat</td>
<td>Write estimates of model parameters in the format of SIMULINK script</td>
<td>DATANAL4.F90</td>
</tr>
<tr>
<td>outanalysis</td>
<td>Summarizes estimates of model parameters of multiple cases</td>
<td>DATANAL4.F90</td>
</tr>
<tr>
<td>outsignal</td>
<td>Write prediction of eye position, velocity, acceleration and active-state</td>
<td>DATANAL4.F90</td>
</tr>
<tr>
<td></td>
<td>tensions</td>
<td></td>
</tr>
</tbody>
</table>
acrforce | Compute active-state tensions | DATANAL4.F90
---|---|---
KAISER | Low pass filter | DATANAL4.F90

| InputData | Input subroutine | Incl.F90
---|---|---
PV_TACB1 | Writes peak velocity vs $\tau_{ac1}$ and $B_1$ into init_pv_tacb1.dat in Tecplot format | DATANAL1.F90
PV_FPB1 | Writes peak velocity vs $F_p$ and $B_1$ into init_pv_Fpb1.dat in Tecplot format | DATANAL1.F90
PV_FPT1 | Writes peak velocity vs $F_p$ and $T_1$ into init_pv_FpT1.dat in Tecplot format | DATANAL1.F90

Table 2-5. DATANAL program subroutines.

The input data type was defined in Incl.F90. The text files *.fiv, *.ten, *.fif and *.twe discussed in the previous section could be read by the subroutine InputData.

Figure 2-26 shows the display when running the FORTRAN program. File name, horizontal saccade and the saccade numbers that are going to be run need to be entered. The program also displays the computed information, and the results will be saved in the output files.

![DATANAL program running](image)

Figure 2-26 (a). Running the DATANAL program, showing the file information entered.
Figure 2-26 (b). Running the DATANAL program, showing the result for a 10° saccade.
After execution, DATANAL primarily generated the output files OUTPUT.OUT, RESPONSE.OUT, SIGNAL.OUT, ANALYSIS.OUT, and SPECPT.OUT. The description for each file’s saved information is listed in Table 2-6.

<table>
<thead>
<tr>
<th>Generated File Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTPUT.OUT</td>
<td>Information of interactions</td>
</tr>
<tr>
<td>RESPONSE.OUT</td>
<td>Information of eye position, velocity and acceleration</td>
</tr>
<tr>
<td>SIGNAL.OUT</td>
<td>Information of neural inputs and active-state tensions</td>
</tr>
<tr>
<td>ANALYSIS.OUT</td>
<td>Estimate of parameters</td>
</tr>
<tr>
<td>SPECPT.OUT</td>
<td>Spectrum results</td>
</tr>
</tbody>
</table>

Table 2-5. DATANAL output files.

These output files could be read by the plotting program DYNPLOT_dv and DYNPLOT_an. DYNPLOT_dv enabled the user to examine the model predicted eye position, velocity, acceleration and neural inputs. As shown in Figure 2-27, the red dots are for the experiment data, the yellow lines are the initial estimates, and the green lines are the final predictions of the model. DYNPLOT_an plotted statistical information of the parameters estimated from multiple numbers of saccades. It automatically loaded ANALYSIS.OUT in current path. An example of DYNPLOT_an is shown in Figure 2-28.
Figure 2-27. DYNPLOT_dv plotting program, visualizing model predicted eye position, velocity, acceleration and active-state tension for a 10° saccade.
Figure 2-28. DYNPLOT_an plotting program, showing the statistical results of duration for 16 10° V-saccades.
2.5.5 Data Deletion and Selection

Since the FORTRAN program was very sensitive to the input files, data was selected before ran in DATANAL. From the plot results in Excel, saccade data with unexpected performance was deleted. The reasons for this included the blinks during data collection that caused the camera unable to track the pupil properly (Figure 2-29 (a)), flutters which made the plots unsmooth because of the parameter adjustment during the setup of the Hi-Speed system (Figure 2-29 (b)). The data of initial eye positions greater than positive or negative five degrees away from the initial target position was discarded since this might be a condition of a previous target movement. FORTRAN also crashed when detected the data that could not meet the requirements, such as saccades with latent period less than 75ms and so on.

![Figure 2-29 (a). Discarded saccade data due to the blink-caused off track.](image)
For all the above reasons, approximately 35% of the collected data was discarded. 486 records of V-saccade, 457 records of AV-saccade and 568 records of A-saccade were finally successfully analyzed in FORTRAN program, and the results will be shown in next section.

The saccadic characteristics values were picked out from the DATANAL output files, and summarized in Excel for plotting and comparison.

3. Results

3.1 Saccade Peak Velocity

The peak velocity of the primary saccades verses saccade amplitude of V-saccade, AV-saccade and V-saccade are shown in Figure 3-1. Peak velocity increases with increasing saccade amplitude as an exponential shape. The relationship fits to the nonlinear equation $v_{\text{max}} = \alpha(1 - e^{-\frac{x}{\beta}})$ as discussed previously.
V-saccade and AV-saccade show a similar property, which typically has peak velocity from 100 degrees per second up to 700 degrees per second. Compared with this, A-saccade has lower peak velocity, and there are fewer saccades with peak velocity over 400 degrees per second at large saccade amplitude.

3.2 Saccade Duration

Sometimes, in order to get more accurate results and conclusions, we divided the saccade amplitude into several sections and analyzed them separately. Here, we found different performance of the duration between small degree saccades and large degree saccades.

As shown in Figure 3-2 (a) and (b), in V-saccade and AV-saccade, duration is approximately constant for saccade under 7 degrees which is around 40ms, while it is linearly proportional to saccade amplitude up to 80ms for saccades above 7 degrees. The trend lines with linear equations are shown on the chart. In A-saccade (Figure 3-2 (c)), the linear relationship exists along all the saccade amplitude. The A-saccade duration is from 40ms to 100 ms, and is longer especially for large saccade amplitude.

3.3 Saccade Latent Period

The latent period verses saccade amplitude is shown in Figure 3-3. It can be seen from the results of V-saccade, AV-saccade and A-saccade, latent period is relatively independent of saccade amplitude. In each kind of stimuli condition, there is a slight increase in mean latent period with saccade amplitude, but A-saccade shows a great variability in the result that between 100ms and 300ms. In general, there is a significant reduction of latent period in AV-saccade, which is from 100ms to 200ms.
Figure 3-1. Peak velocity vs. saccade amplitude: (a) V-saccade. (b) AV-saccade. (c) A-saccade.
Figure 3-2. Duration vs. saccade amplitude: (a) V-saccade. (b) AV-saccade. (c) A-saccade.
Figure 3-3. Latent period vs. saccade amplitude: (a) V-saccade. (b) AV-saccade. (c) A-saccade.
3.4 Saccade Accuracy

From the plotting results shown above, there are more obvious boundaries between 5°, 10°, 15° and 20° data in V-saccade and AV-saccade than A-saccade. It indicated that the AV-saccade exhibited the greatest saccade accuracy. This was followed by the V-saccade. The least accurate was the A-saccade.

3.5 Agonist Pulse Magnitude and Duration

The results of agonist pulse parameter estimation are shown in Figure 3-4 and Figure 3-5. In V-saccade, AV-saccade and A-saccade, agonist pulse magnitude shows a linear increase from 0.5N to 1N for small saccades less than 7 degrees, while presents a less significant linear increase in large saccade amplitude. For saccade amplitude around 10 degrees, agonist pulse magnitude is relatively constant.

Agonist pulse duration is relatively constant at 10ms in small saccade amplitude less than 7 degrees. There is a linear increase in larger saccade amplitude.

There is not much difference of the agonist pulse parameters between V-saccade and AV-saccade. However, A-saccade exhibits lower agonist pulse magnitude and longer agonist pulse duration in saccades between 12 and 20 degrees.

3.6 Post-Saccade Behavior

A post-inhibitory rebound burst (PIRB) in the antagonist motoneurons caused the post saccade phenomena, such as a dynamic or a glissadic overshoot (Enderle and Zhou, 2010). Table 3-1 shows a statistic of the post-saccade phenomena that happened during the testing. Either a dynamic overshoot or a glissadic overshoot occurred in 50.4% of the V-saccades, 65.65% of the AV-saccades, and 76.76% of the A-saccades. Approximately
65% of all the saccades that we recorded for the study contained a post-saccade phenomenon and it occurred quite randomly.

There was a higher incidence of overshoots, especially the dynamic overshoots, in A-saccades. Moreover, dynamic overshoots happened more often in the abducting direction than the adducting direction saccades. In the results of the left eye in A-saccade, 72.64% of the left direction saccades contained a dynamic overshoot, while it could be found only in 29.29% of the right direction saccades. In V-saccade and AV-saccade, such similar performance of the overshoot incidence was also exhibited from the data.

In the following sections, the characteristics of post-inhibitory rebound burst will be shown. In the charts, “Glissade” means the glissadic overshoots, “Overshoot” indicates the dynamic overshoots, and “Normal” presents the regular saccades that have no post saccade phenomena.

<table>
<thead>
<tr>
<th>Saccade Type</th>
<th>Total Number</th>
<th>Nomal Saccade</th>
<th>Dynamic Overshoot</th>
<th>Glissadic Overshoot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>% of V</td>
<td>No.</td>
<td>% of AV</td>
</tr>
<tr>
<td>V-saccade</td>
<td>486</td>
<td>241</td>
<td>157</td>
<td>18.11%</td>
</tr>
<tr>
<td>AV-saccade</td>
<td>457</td>
<td>157</td>
<td>195</td>
<td>22.98%</td>
</tr>
<tr>
<td>A-saccade</td>
<td>568</td>
<td>132</td>
<td>309</td>
<td>22.36%</td>
</tr>
</tbody>
</table>

Table 3-1. Statistic of post-saccade phenomena.

3.6.1 Post-inhibitory Rebound Burst Magnitude and Duration

Figure 3-6 and Figure 3-7 provide estimates for the PIRB in the antagonist motoneurons, where the PIRB induces a reverse peak velocity, and the features are similar in V-saccade, AV-saccade and A-saccade. Normal saccades usually do not have a notable rebound burst.
Figure 3-6 shows the relationship between PIRB magnitude and saccade amplitude. Dynamic overshoots have the largest PIRB magnitude which is between 0.3-0.6N, while glissades have PIRB magnitude between 0.3-0.5N. Normal saccades have small rebound burst between 0.2-0.4N, and display an inversely linear proportional function to saccade amplitude.

As shown in Figure 3-7, PIRB duration of dynamic and glissadic overshoots falls in 8-14ms, with considerable variation for the same saccade amplitude.

3.6.2 Antagonist Onset Delay

In Figure 3-8 and Figure 3-9, antagonist onset delay is plotted against saccade amplitude as well as PIRB magnitude. Antagonist onset delay is typically 2-35ms, and small saccades have shorter onset delay while large saccades have longer onset delay. Moreover, antagonist onset delay is longer in A-saccade compared with the V-saccade and AV-saccade that of the same size.

At the same time, from the plot of antagonist onset delay, it is shown that normal saccades are clustered closer to the origin, while moving further from the origin, glissades cluster in a band followed by saccades with a dynamic overshoot.
Figure 3-4. Agonist pulse magnitude plot: (a) V-saccade. (b) AV-saccade. (c) A-saccade.
Figure 3-5. Agonist pulse duration plot: (a) V-saccade. (b) AV-saccade. (c) A-saccade.
Figure 3-6. PIRB magnitude vs. saccade amplitude: (a) V-saccade. (b) AV-saccade. (c) A-saccade.
Figure 3-7. PIRB duration vs. saccade amplitude: (a) V-saccade. (b) AV-saccade. (c) A-saccade.
Figure 3-8. Antagonist onset delay vs. saccade amplitude: (a) V-saccade. (b) AV-saccade. (c) A-saccade.
Figure 3-9. Antagonist onset delay vs. PIRB magnitude: (a)V-saccade. (b)AV-saccade. (c)A-saccade.
4. Discussion

4.1 Basic Saccade Characteristics

In most results, characteristics of V-saccade and AV-saccade are similar. This is because visual targets are much easier to follow, and subjects react to and locate the stimuli’s positions mainly upon the visual cues. But at the same time, property differences still can be seen among the three types of stimuli induced saccades.

The studies of Zahn et al. (1978), Engelken et al. (1989) and LaCroix et al. (1990) presented that auditory saccades were slower of lower peak velocity and longer duration, as well as less accurate than visual saccades. Our results are in agreement with these conclusions. We find that the auditory stimuli produce saccades with 10% - 20% lower peak velocity and around 15% longer duration than visual and auditory-visual bisensory stimuli, especially in large saccade amplitude. According to LaCroix et al. (1990), this can be explained by the fact that a smaller population of cells in the superior colliculus is active before A-saccade than that is active before V-saccade. Saccade velocity is related to the size of the population of the active superior colliculus cells before a saccadic eye movement (Lee, Rohrer and Sparks, 1988). Fewer cells in the superior colliculus are responsible to sound stimuli and fewer cells show motor activity before an auditory saccade (Jay and Sparks, 1987), thus generate saccades with lower peak velocity and longer duration.

The results and the comparison of saccade latent period are a little bit complicated. The slight increase of latent period with saccade amplitude in V-saccade is consistent with the previous studies by Zahn et al. (1978), Engelken et al. (1989). However, in our A-saccade results, there is no obvious decrease of latency with increasing target
eccentricity as presented by Zahn et al. (1978), Engelken et al. (1991). We find a great variability of latent period happens in A-saccade, and it is independent of saccade amplitude. This may be due to the fact that the detection of sound onset is faster than visual stimuli for humans, but it requires more processing time to locate the sound source. Another reason may also affect this, that the presentation of the auditory signals will influence the performance of the subjects. But in general, AV-saccade shows a significant reduction in latent period, since a sound onset cue facilitates the response time.

4.2 Agonist Pulse

In our study, in order to provide more accurate analysis, we divide the saccades into three sections, which are saccades under 7 degrees, saccades around 10 degrees and saccades larger than 12 degrees. The studies of Enderle and Zhou (2010) showed that in V-saccade, the estimated agonist pulse magnitude didn’t significantly increase with increasing saccade amplitude for saccades larger than 7 degrees, but there was a more obvious linear increase for small saccades under 7 degrees. Our result is in agreement with this for small and large saccade amplitude, which are also consistent with the time-optimal controller proposed by Enderle (2002). In addition, we find that for saccades around 10 degrees, the agonist pulse magnitude is relatively constant. In A-saccade, even though we don’t get many saccades with agonist pulse magnitude that is less than 0.5N as presented by LaCroix et al. (1990), we still find that for large saccade amplitude, many auditory saccades have lower agonist pulse magnitude than visual saccades, which is less than 1.2N. And in all types of saccades, a great variability is observed in the agonist pulse magnitude estimation for saccades of the same amplitude.
Tightly coordinated with the agonist pulse magnitude, the result of agonist pulse duration is also consistent with previous studies, which is constant in small saccade amplitude while there is a linear increase in large saccade amplitude.

Saccade peak velocity and duration are primarily related to agonist pulse magnitude (Ender and Zhou, 2010). There is a reduced recruitment of neurons innervating the agonist muscle during auditory stimuli induced saccades (LaCroix et al., 1990). The lower magnitude and longer duration of agonist pulse in A-saccade can explain the lower peak velocity and longer duration of auditory saccades.

4.3 Post Saccade Phenomena

When a neuron is seriously inhibited and then released without stimulus, a high-frequency burst fires and ends after a short period of time. Thus, the inhibition of antagonist burst neurons is supposed to cause a post-inhibitory rebound burst (PIRB) at the end of a saccade, and then initiates a post saccade phenomenon such as a dynamic overshoot or a glissade. In the theory presented by Enderle and Zhou (2010), at least in humans, the antagonist PIRB causes a reverse peak velocity during dynamic overshoots or glissades. Similar to the results provided by LaCroix et al. (1990), Enderle and Zhou (2010), we can find more saccades with an overshoot in the abducting direction of the eye movements than in the adducting direction of the eye movements, no matter in V-saccade, AV-saccade or A-saccade.

Neurons that fire at steady rates during fixation are called tonic neurons (TN). It depends on the eye position and is thought to provide the step component to the motoneurons. Excitatory burst neurons (EBN) and inhibitory burst neurons (IBN) describe the synaptic activities on the neurons. The EBNs excite and are responsible for
the burst firing while the IBNs inhibit and are responsible for the pause. During an abducting saccade, ipsilateral abducens motoneurons fire without inhibition, while oculomotor motoneurons are inhibited during the pulse phase. Since the IBNs inhibit the antagonist motoneurons, the resumption of TN and PIRB activities will not begin until after the ipsilateral IBNs stop firing. Moreover, a greater number of internuclear neurons exist and operate during an abducting saccade. There is a longer time delay before the resumption of activities in the oculomotor motoneurons after the pulse phase for abducting saccades than adducting saccades (Enderle and Zhou, 2010). All of these lead to the results that there are more overshoots can be found in the abduction direction. And such phenomena happen more often in auditory saccades.

However, we don’t find significant decrease of dynamic overshoot incidence when saccade amplitude increases. But such relationship is shown for glissade. According to Enderle and Zhou (2010), this is related to that fewer saccades have sufficiently high PIRB magnitude as saccade amplitude increases.

4.4 Experiment Design

4.4.1 Subjects Limitations

Since the data of the experiments mainly comes from two subjects, limitations exist for the analysis. Even though most of the results are consistent with previous studies, data from more subjects will provide a more theoretical stringency. Ideally, six to eight subjects with around 500 saccades recorded for one experiment (V-saccade, AV-saccade or A-saccade) per person could make the results more airtight.

4.4.2 Auditory Stimuli Limitations
The design of the auditory stimuli of this work may have influence on the results of the experiments that contain auditory targets, especially for A-saccade. How a subject response to the sound cue is related to the acoustic features, which are frequency, intensity and spatial location, as well as the sound type. According to Gabriel et al. (2010), saccade latency would be shortest for wideband noise and narrowband noise with center frequencies falling within the human speech range. Thus, to induce the experiments with different types of sound cues may intensify the validity of the results.

4.4.3 Stimuli Presentation

The ability for humans to localize sound is limited due to our physiological makeup. The best 3D positional audio software is still limited by sound localization errors. What’s more, since the distance between the stimuli monitor and the subject is close, and the positions of auditory stimulus need to be corresponded to the visual stimulus that shown on the monitor, it’s hard for subjects to tell the correct location of the sound source, especially for small saccade degree targets. In order to provide a more practical presentation of auditory and visual stimuli, a large scale speaker and LED matrix is expected to induce the experiments. This is currently designed by another group. The comparison between the performances may lead to a more well-rounded analysis.

5. Conclusion

Saccades are very fast eye movements that used to acquire a target and center the visual image on the fovea. The work presented in this paper provided a comprehensive analysis of horizontal goal-oriented saccadic eye movements. Human saccades in response to visual stimuli, auditory stimuli and auditory-visual bisensory stimuli were
recorded by a high speed eye tracking system. The data was analyzed with a program written in FORTRAN language, which was used to compute parameter estimates for a horizontal saccadic eye movement model.

Saccade characteristics were investigated, and the results of saccades that induced by the three different stimuli types were compared. The auditory-visual stimuli provided the greatest saccade accuracy. Saccade peak velocity increased with increasing saccade amplitude as an exponential shape. Saccade duration was linearly proportional to saccade amplitude. Auditory saccades showed lower peak velocity and longer duration. Saccade latent period was relatively independent of saccade amplitude, but there was a significant reduction in the bisensory saccades.

Moreover, auditory saccades exhibited lower agonist pulse magnitude and longer agonist pulse duration in large saccade amplitude. Post-inhibitory rebound burst caused the post saccade phenomenon. Antagonist onset delay was longer in auditory saccades for the saccades that of the same size. There was a higher incidence of dynamic overshoot in auditory saccades, while more in the abducting direction than the adducting direction.

6. Future Directions

In order to get a comprehensive analysis of the saccadic eye movement system, more experiments need to be designed and performed. Beyond the goal-oriented horizontal saccades, we are currently working on the horizontal double-step saccades, as well as the horizontal anti-saccades.

As described before, a double-step saccade means two successive stimulus targets are provided, thus the subject will make a sequence of responses to the targets. This type of saccades has rarely been presented before by other researchers. The general idea of our
current design is that, we perform two types of stimulus sequences, which are center-five-ten degrees and center-ten-twenty degrees. The duration of the center target and the second peripheral target is similar to the goal-oriented saccade experiment design, which is randomly from 3000ms to 5000ms. However, we set up the first peripheral target for 70ms, 140ms, or 210ms. This is because we suppose that for a short presentation of the first peripheral target, one single saccade will happen instead of the occurrence of a double-step. There is an expectant significance for analyzing the characteristics of the second step in the saccades. The neural network for double-step saccades is different from the regular goal-oriented saccades. The comparison of the first step saccades and the second step saccades, the second step saccades and the regular saccades will lead to a deep investigation of the neural control for saccades.

Anti-saccades indicate that subjects need to make a saccadic eye movement to the opposite direction of the source target. This requires a more complex procedure for the brain to perform the saccades, thus the saccade latent period will be longer than regular saccades. Patients with a variety of cerebral lesions, especially ones involving the eye fields of the frontal lobes, will show abnormalities on the anti-saccades task. They are unable to make a reflexive saccade towards the target and have difficulty generating a voluntary saccade toward an imagined location (Leigh and David, 1999). Thus, the study of anti-saccades will provide a reference for clinical illness diagnosis and analysis.

In order to be consistent with the realistic environment, beyond horizontal saccades analysis, vertical saccades as well as three-dimensional saccades will also be performed. What’s more, a large LED and speaker matrix will be used instead of the monitor-
headphone visual-auditory stimulus pattern. This will lead a more practical presentation of the stimulus targets and the results can be compared with the previous data.

All the experiment design and data collection are the fundamental base for the study of saccadic neural network. Currently, the neural network for visual stimuli induced saccades have been investigated extensively, however, much less is known for the neural network of auditory saccades. This will also be one of the major directions for the future work. The visual and auditory sensory systems of humans need further investigation.
7. Appendix

7.1 List of Publications


References


