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Experimental testing of a sensorimotor origin of saccadic suppression

Dissertation presented by
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Abstract

Saccades are essential eye movements for our environment construction but such rapid and numerous movements are subject to phenomena which have repercussions on perception. It has been known for a while that around the saccade timing there exist a lost of visual sensitivity, this effect is known as saccadic suppression. Its origin and mechanism are still subject to debate but the prevailing hypothesis suggests that saccadic suppression is a phenomenon purely related to the stabilisation of perception. However, elements such as the timings of suppression make this assumption inconsistent. Here for this work we propose to test a novel hypothesis which seems to respond to the critics. This hypothesis claims that saccadic suppression could arise from an efficient sensorimotor calculation and consequently that there could be a cross talk between perception and control in the brain. In other words this hypothesis states that perception can be impaired by sensorimotor control, consequently a way to challenge it is to consider that control might be impaired by perception. To do so, we realised an experiment with several subjects where we tried to disrupt their saccade movement with flashed stimuli.

We analysed the recorded eye movements of each subjects and particularly their saccade main sequences. Many very uncommon anomalies in these saccades were found which is in agreement with what the hypothesis stated. Our results tend thus to confirm the sensorimotor origin for the saccadic suppression. However future analyses are still needed to clarify the link between these anomalies and other parameters.

Contents

Chapter 1

Introduction

1.1 General introduction

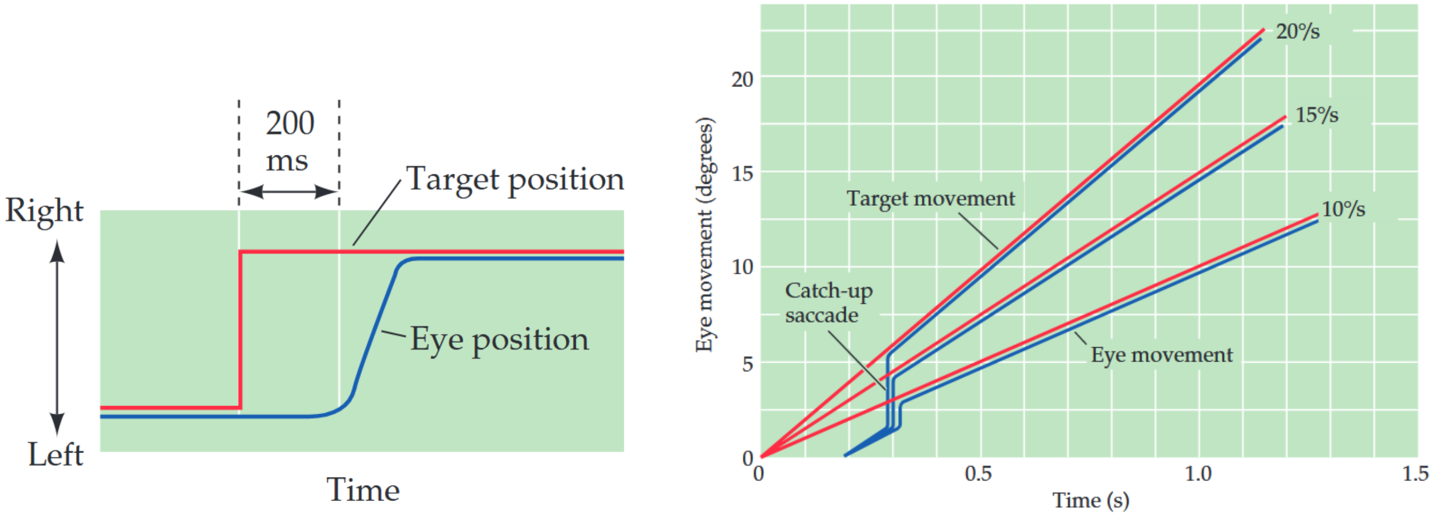
Vision is a crucial sense in the human being as it allows to represent the environment accurately and ease interactions with it. This particularly precise vision is linked to the presence of the fovea. Fovea is a region of the retina where the cone cells density (the photoreceptors responsible for fine vision and colour perception) is very high and so our visual acuity. The rest of the retina is mainly compose of rod cells that are responsible for low intensity vision but which are still essential.

Fovea is a first element explaining our high visual acuity but it does not explain the ease we have to build a global environment perception. A second important element to take into account is the way we position our gaze over our environment. Different stereotyped sequences of eye movement have been identified, each having a specific role and a particular neuronal pathway. Generally we separate them in 4 kinds:

1. **eye saccades** are quick movements of the gaze that allows for example to reposition our gaze or catch a target. The goal of a saccade is to rapidly bring the fovea on the desired target. Saccades are thus the fastest kind of eye movement, they last on average about 50 ms and their typical velocity peaks are between 400 and 800 $°/s$. This kind of eye movement is generally automatic and not noticed (we use it three times a second on average) but can also be voluntary. An example of typical 1D saccadic movement is given in figure 1.1a, we can notice the sensorimotor delay between the appearance of the target and the beginning of the saccade.

2. **smooth pursuit movements** consist in continuous eyes rotation allowing to keep the fovea on a small moving target. Generally smooth pursuit is considered as voluntary eye movement since it is possible to chose whether or not to follow the target. However it is quite difficult to start a smooth pursuit movement without a target to track. Smooth pursuit velocity adapts to the target velocity and are often preceded by saccades to rapidly compensate the error of eye position when target starts moving (figure 1.1b).

3. **vestibulo-ocular movements** stabilise images on the retina by producing an eye rotation in the opposite direction of the head movement to exactly compensate it. Vestibulo-ocular movements are due to the collaboration between eye motor function and sensory information given by the vestibular system. These movements are thus reflexes preventing image perturbation caused by head movements.



(a) Saccade movement

(b) Smooth pursuit movement

Figure 1.1: Eye movement is in blue; target position is in red. Images were taken from reference [12]

4. And finally **vergence movements** occur when the depth of the target changes, causing a change of angle between the two eyes in order to align the fovea of each eye on the desired target. The eyes will thus converge for a close target and diverge for a target moving away.

All these movements complement well each other, allowing us to easily build a representation of our environment and update it effectively. These movements have been examined in many studies which try to understand the links and interaction that can take place between different parts of the brain. In the context of this master thesis, we propose to focus on the ocular saccade and on a typical phenomenon occurring during it: **the saccadic suppression**

1.2 Saccadic suppression

As stated previously we use saccades very often in daily life without noticing it. In fact saccade is the most prominent eye movement for our environment construction. It captures quick snapshots to finally build a coherent representation. To do so it has to face several challenges such as for example link representation before and after saccades or allow to discern difference between the retinal motion and real object motion as indicated by Ibbotson and Krekelberg [5]. It is thus non surprising to observe particular phenomena occurring around the time of saccade. Among these phenomena one of the most studied is the saccadic suppression. It has been known for a long time that during eye saccades there exists a reduction of visual sensitivity and that part of the visual information is lost. It is specially the case when we have to detect objects that start to move around the saccade beginning. Many studies showed that for different kind of flashed stimulus during saccades (gratings, spots of light, bars, ...) visual sensitivity decreases [14] and alters the perception. These studies also show this effect is particularly dependent on several parameters such as contrast, luminance or spatial frequency. It is known as **saccadic suppression** and nowadays its purpose and mechanisms are not yet clear.

Saccadic suppression has often been associated with compensation for movement-related shifts of the visual scene, thereby maintaining a stable perception of our environment [16].

However it has been established that it occurs more than 50 ms before saccade onset and can continues nearly 50 ms after the end of the movement [5] [3] [14]. In comparison, a 20° saccade lasts for about 50ms, hence a suppression of 100ms is about twice as long as the movement duration and represents an important information loss which really questions the true reason of this phenomenon. If it was purely to stabilise the retinal image saccadic suppression seems thus extremely inefficient. Moreover, some papers studied the intensity of suppression when subjects fixated an image being displaced very rapidly as if there was a saccade, but without a saccade (with a mirror for example) and showed that suppression was not as strong as usual [3][15] which indicates that suppression is not only link to eye motion.

Concerning the origin of this phenomenon, in the past it has been proposed that this effect could primarily originate from the retina under the assumption that photoreceptors may collect less light during saccades [9]. However for the same reason as above, the saccadic suppression could not arise purely from the retina. The different papers we cited above tend to show that saccadic suppression seems to be a centrally-controlled mechanism that is not purely tight to motion-related loss of information.

Nowadays if the location of the phenomena in the brain is quiet generally accepted, the different parts of the brain which are involved as well as the mechanisms are still subject to debate.

1.3 Context and goals

1.3.1 Context

The origins and complete purpose of saccadic suppression are thus still quite confuse. F. Crevecoeur and K. P. Kording were interested to eye control and its link with perception [1]. They started from the problems stated above: suppression timing is unnecessary long if it is purely to stabilise vision during eye saccade; simulating the motion of the retinal image without saccade does not lead to similar suppression. To inspect the control of the eye plant they chose to build a mathematical model theoretically able to reproduce its main properties (see figure 1.2). To reproduce classical eye plant behaviour and observed saccadic suppression timings, they took into account 3 main eye properties:

- Retinal information takes time to go to motor neurons (i.e the delay between retina and neuron is non negligible).
- There is a signal dependent noise when neuron generates motor command.
- There is still a sensory feedback during saccade able to influence the motor command.

It consists of a closed-loop model where the controller outputs motor commands by comparing target location and estimated state. The state estimator as its name suggests estimates the state of eye plant i.e the supposed current eye position. The motor command is thus adapted according to the difference between the desired location and the estimation of the current location. The state estimator is here based on 2 main elements: corollary discharge and delayed sensory feedback. A key element of the model is that through computation of the state estimator the sensory feedback is combined with corollary discharge to obtain a sensory extrapolation, this extrapolation is then modulated by a Kalman gain and participate to the estimation of the current state. This Kalman gain is inversely proportional to the variance, thus the more variance the less the contribution of position feedback for the estimation state. This is the main concept that will be use to propose another hypothesis for saccade suppression.

They showed that their model was able to correctly simulate a saccadic eye movement as well as a smooth pursuit movement. They also showed their timings of saccadic suppression seemed to respect the classical observed timings in literature (see figure 1.3b). These suppression

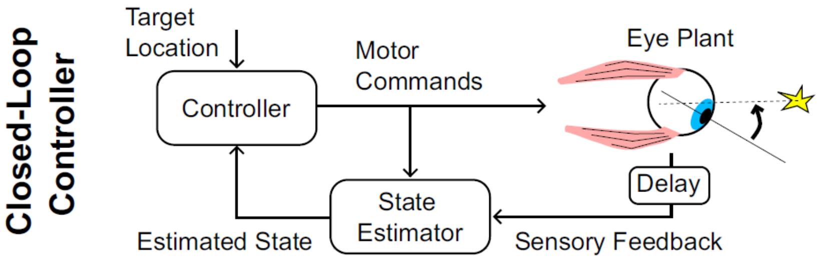
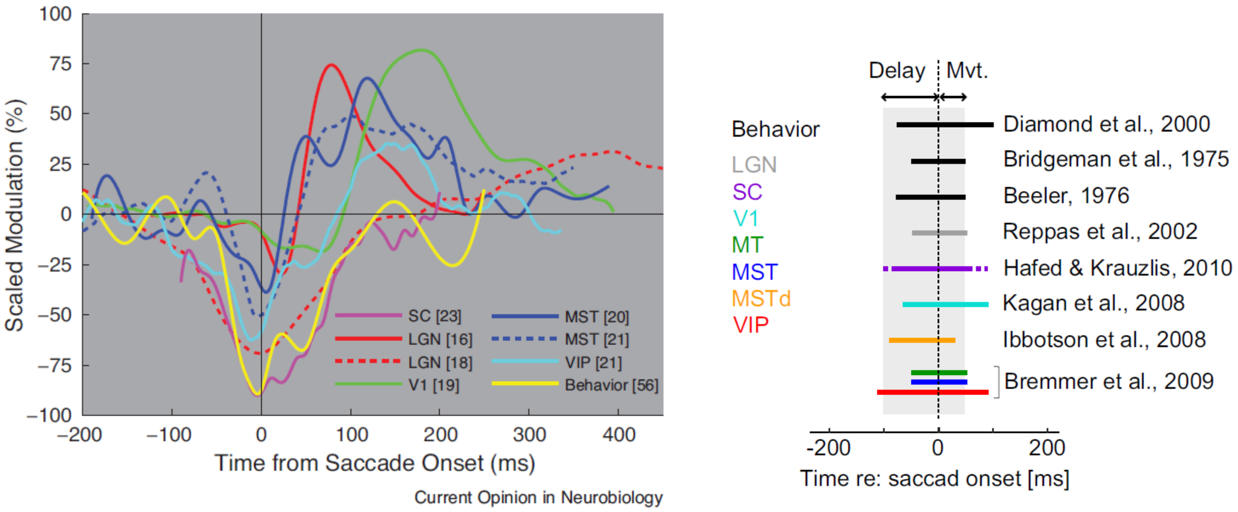


Figure 1.2: Crevecoeur and Konrad’s model [1]

timings comes from what is observed in different parts of the brain. The values correspond to the modulation of the average neurons firing rate which can be observed on figure 1.3a. The only curve which does not reflect the neurons firing rate is the behavioural curve showing the evolution of perception performance in comparison to what is achieved during fixation. This curve allows to highlight the link between behavioural response and neuronal response. These values are then extracted to compare the different timings with the suppression timing of their model (on figure1.3b).

On the basis of their model they formulated a different hypothesis of saccade purpose. As stated above they took into account that our muscles produce signal dependent noise. This means if we want to produce a saccade the motor command also produces noise and we end up with a visual uncertainty. At this point, the variance of the extrapolation is high but we have to recall the Kalman gain is inversely proportional to this variance and thus decreases the feedback weight as the variance increases. This reduction of weight in the sensory feedback would therefore correspond according to this model to the cause of saccadic suppression. Following this reasoning saccadic suppression appears to be a way for the brain to optimise the control of saccade movement. The authors finally suggest that, since saccadic suppression could come from an efficient sensorimotor calculation then control of eye movement and perception may share common regions in the brain.



(a) Response modulation in different part of the brain[5]

(b) Comparison of suppression timings [1]

Figure 1.3: Timings of suppression in different parts of the brain and comparison with timing suppression of the model

1.3.2 Goal of the work

Nevertheless their research has only be conducted on control model and it still needs experimental validation. In their paper Crevecoeur and Kording proposed a possible way to test their assumption. They suggested that, since perception can be impaired by sensorimotor control it could be possible that control might be impaired by perception. To do so they have evoked one way to do it:
«*if it were possible to train participants to pay attention to visual stimuli displayed during saccades, thereby increasing the weight of sensory feedback, then the theory predicts that movement trajectories should become more variable as a result of suboptimal state estimation.*»[1]

This is what has been done for this master thesis. Indeed the purpose of this work is to challenge their assumption about saccadic suppression by realising the test task they proposed. To do so we built a task where the subjects had to make horizontal saccades from a target to another. During the saccade a stimulus was displayed. This stimulus had 3 possible inclinations and subjects had to give an answer about the particular inclination. To motivate subjects to really pay attention during this detection task they were remunerated according to their performance at discriminating the good orientation of the stimuli. By doing so we wanted to stack all the odds in our favour at trying to increase the weigh of sensory feedback as expected. The experience is described more in detail in the section materials and method. Then the results section analyses how the experience was achieved and if data are highlighting uncommon behaviour which could validate or invalidate Crevecoeur and Kording's hypothesis.

Chapter 2

Materials and methods

As explained in the introduction our goal was to build a task increasing the weight of sensory feedback during saccades. For this part we explain how we proceeded to build such a task. The goal here was to make sure that we had a good basis so that we could then draw the most reliable conclusions regarding the hypothesis on saccadic suppression previously stated. This section will thus detail and explain more precisely the experience protocol as well as the materials and key elements used for the realisation of this experiment. We also will precise the few post-processes we applied to our data as well as the tools we used to characterise the velocity profiles.

2.1 Materials

For this experiment an Eyelink 1000 tracking device was used to track the eye position. This device allow to sample the eye position each millisecond. A Barco cine 8 projector was used to display the targets and stimuli on a white screen. The displayed experiment was at a resolution of 800 pixels width and 600 pixels height and at a 100Hz rate. The experiment scripts was written in MATLAB, using the Psychophysics Toolbox extensions [7] and running on the 7.1 MATLAB version.

The tests participants were sitting in a dark room at 1.5 m from the front of the screen. In order to prevent any important change of the head position during the experiment their head was blocked with a headrest.

2.2 Methods

2.2.1 Protocol

The experiment was separated in 8 blocks of 60 flashed visual stimuli with 1 to 3 minutes rest between each block. For all blocks, subjects had to detect the orientations of the displayed stimuli. Before starting the first block they were notified the only possible orientations were 0°, $-5°$ and $+5°$. The first block was the only one without required saccadic eye movement.
We will first describe the two kinds of block that were used during this experiment before moving on to the concrete progress of the experiment.

The first kind of detection block consisted in automatically flashed stimuli right in front of the subject ("no saccade block"). The stimulus display duration was one frame i.e. about $10ms$. After each stimulus display the subject had to give its opinion about the stimulus orientation by pressing the corresponding key on the keyboard next to him in less than $1.5s$, the next stimulus was display a few seconds later and so on.

For the second kind of block ("saccade block") stimuli were no more automatically flashed in front of the subjects. They had first to make eye saccade from a target to another and during the saccade the stimulus was displayed. The target was randomly set at $-10°$ or $+10°$ on horizontal axis ($0°$ being straight ahead them). After a certain random time the target position switched to the opposite side i.e. $+10°$ if it was first at $-10°$ and $-10°$ if it was first at $+10°$. It was asked to the participants to follow the red target and when subject's saccade to the second target was detected the stimulus was as fast as possible displayed during one frame. As for the "no saccade block" the subjects had to give their opinion about the stimulus orientation after each stimulus display.

Each block was also preceded by a calibration task where subjects had to follow green dot target displayed at 8 different cardinal positions in order to later correct possible mis-calibration of Eyelink. The display of these targets included a horizontal target switch from $-10°$ to $+10°$ which will be used as reference saccade course for the further analysis.

The first step of the experiment was about comparing the score for subject's stimulus detection with and without saccadic movements. To do so we used a "no saccade block" for the first block and then a "saccade block".
For the second step the purpose was to repeat many times (i.e. 7 times) a saccade block to let subjects learn the task and improve their score for each new blocks. Knowing there was already a saccade block during the first step we only repeated the saccade block 6 times to have our 7 saccades blocks (the timing rest between first saccade block and second is still 1 to 3 minutes). From the first block of this step (thus the second saccade block) subject's were told that their remuneration for this experiment would be proportional to their score. This was done in order to motivate them and to be sure they will stay the most focused they could. After each block they were told their detection score and how much their performance was paid before starting the next block. The experiment ended after the subject gave his answer for the 60th stimulus of the 8th block

2.2.2 Saccade detection

The Eyelink device proposes a detection saccade feature however due to our timing constraints this detection was not fast enough. We thus implemented a detection saccade that suited better to our needs. The used saccade detection criteria was the eye velocity, in order to compute this velocity a second order upstream numerical derivative of the eye position was used as followed:

$$v(t_i) \approx \frac{3x(t_i) - 4(x(t_i - h) + x(t_i - 2h)}{2h}$$

where $x(t_i)$ is the eye position expressed in degree at time t_i, and h is the chosen timing step expressed in second. Here since the eye tracker allow us to sample the eye position each millisecond, h=10^{-3} s was chosen.
The chosen condition to admit eye saccade at instant t_i was that the eye velocity should be larger than 230 $°/s$ for 2ms i.e. as soon as we have $v(t_{i-1}) > 230°/s$ and $v(t_i) > 230°/s$. This condition has been set after several offline tests on different dataset in order to have a detection fast enough with a false positive detection rate tending to zero. The detection could be faster by lowering the velocity threshold but this will be at the cost of getting possible false positive detection. This is illustrate on figure 2.1 where we clearly saw the difference between a velocity threshold of $230°/s$ and $150°/s$. In the second case false positives during eyes fixation on target are really too present and would represent a bias for the later analysis.

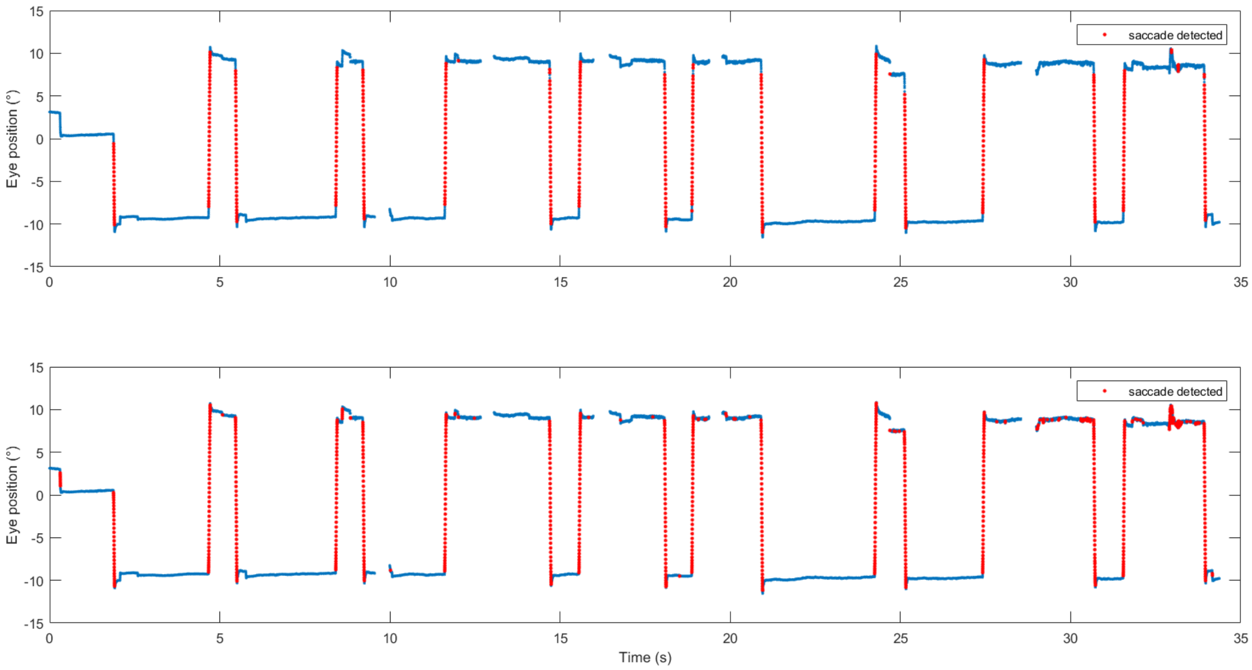


Figure 2.1: Comparison of the velocity threshold for saccade detection

upside: threshold$= 230\ ^{\circ}/s$; downside: threshold $= 150^{\circ}/s$

2.2.3 Displayed stimuli and targets

Here we will have a closer look at the elements that were displayed to subjects. We will essentially focus on the design of the stimulus.
But before we can have a word concerning the fixation targets. We chose red filled circles of 4 pixels radius and separated each other from 20°. By doing so the targets occupy only a very small part of the field of vision while still being easy to perceive.

Concerning the stimulus, Gabor patches with three different orientations were used (see figure 2.2). They were drawn thanks to piece of code from the Psychtoolbox that we adapted to our needs.

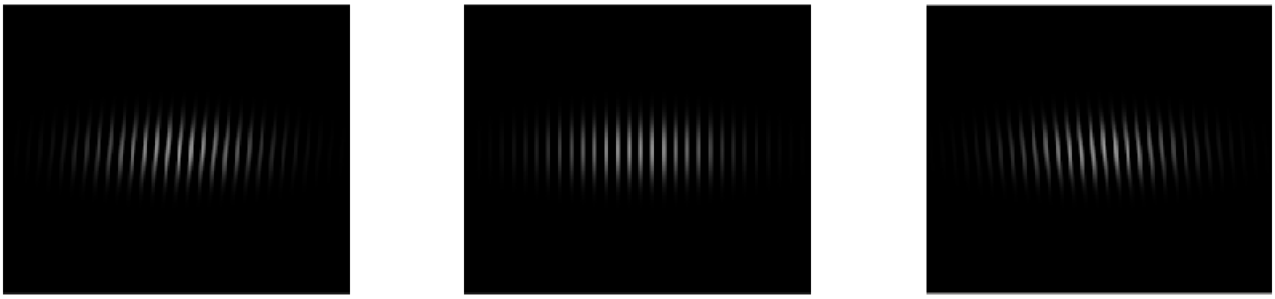


Figure 2.2: left: -5° tilt angle, mid: 0° tilt angle, right: $+5^{\circ}$ tilt angle

To assess the difficulty and relevance of stimuli detection during saccade we previously tuned the main parameters according feedback of 3 different people which had to detect it in both experiment block conditions:

1. The stimuli were flashed right in front of the participant without them needing to perform a saccade(no saccade block).
2. The stimuli were flashed only during saccades (saccade block).

We then collected feedback and success detection rate of these three people. The goal was to have a detection rate between 90% and 100% (i.e. to obtain an trivial task) for the case without saccade and between 35% and 50% for the second case (i.e. to obtain a challenging task when considering saccadic suppression).

The tuned parameters were size, spatial frequency, ratio of the Gaussian envelope, contrast and angle of inclination.
For the size due to our timing constraints (see a bit below) it has been decided to make a relatively large stimulus to be sure it would always be displayed close to the center of field of view. We thus selected a size of 250*300 pixels corresponding to 26.07 ° of field view in the experiment condition in order to cover a large region between $-10°$ and $+10°$. It has to be noticed that this size corresponds to the entire picture of the stimulus showed on figure 2.2 thus the visible part of the stimulus covers only a moderate region of the picture. We proceeded in the same empirical way for the other parameters by keeping in mind the difficulty of both blocks. At the end we chose a spatial frequency of 0.1 cycle/pixel, a Gaussian envelope 5 times wider in horizontal than vertical, a contrast in grayscale from 0 to 57% (100% being white), and -5/+5 for the tilt angles.

Concerning the timing of stimulus display the objective was to be able to flash it during the ocular saccade. However knowing that a 20° saccade last at most 100 ms, that there is some delay between saccade onset and detection (see figure 2.1) and that our display frequency was 100 Hz, this leads to non negligible display delay. After some trials we realised that due to these technical constraints our minimum delay to flash the stimulus was $\sim$ 40 ms after a saccade beginning. This means that for a 20° saccade the stimulus can be displayed on average after the eye has travelled approximately 10°. Thus to be sure the stimulus would be in the subject's field of view (despite some variance in saccade duration) we decided to always display it at $x = 0$ and to make it large enough to cover reasonable length. These 2 conditions was set to try to maximise the visibility of the stimulus even if the eye position at time of display deviates from $x = 0$. A scaled picture of the screen with all elements displayed is shown on figure 2.3.

Concerning the proportions of stimulus orientations, since it is known that saccade direction can influence the perception of visual stimulus [10] we chose to display 10 times each of the three stimuli for both saccade direction. This leads to 30 trials where saccades go from -10° to +10° and 30 trials where saccades go from +10° to -10° meaning a total of 60 trials for each blocks.

Finally it has to be noticed that we set a small vertical offset of -20 pixels from the middle of the screen for all displayed elements. This has been done in order to keep these elements approximately at the same height than the subject's eyes but also to be sure the Eyelink device placed just above subject's head would not hide any element.

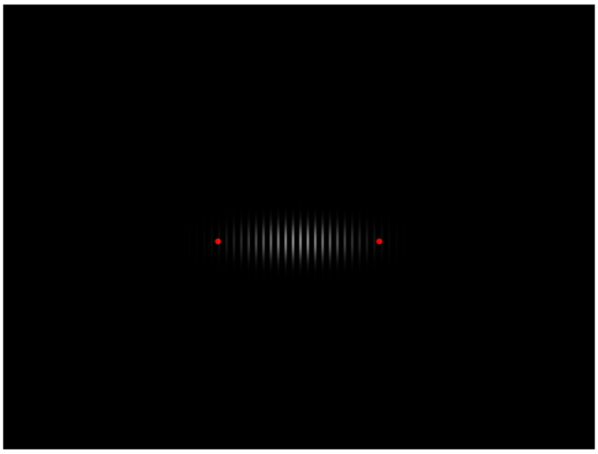


Figure 2.3: Scaled picture of the experiment screen when all elements are displayed

2.2.4 Subjects

Twelve people performed the experiment. Subject's age varied between 22 and 24 years. Three subjects wore glasses and one wore lens. Among them 2 suffers from myopia and astigmatism and the 2 others suffers only from myopia. The rest of the subjects had normal vision. The experience approximately took 1 hour and 10 minutes per person, and a block lasted approximately 7 minutes.

2.2.5 Data post-processing

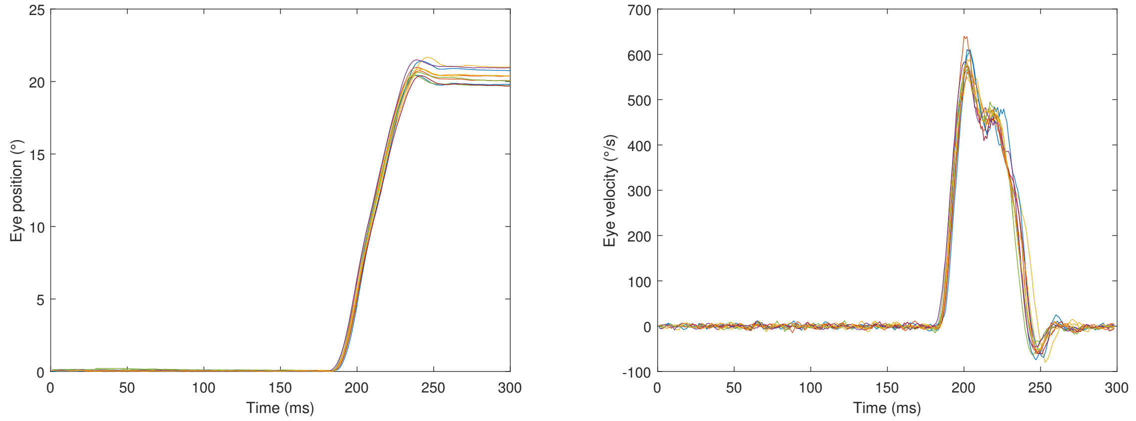
To extract useful information from our collected data we apply some post-processing operations on our dataset.

First we chose to do not take into account any saccade information when subject did not give answer about stimulus orientation. There were different possible cases leading to no orientation answer given:

1. Subject anticipated target switching and thus no saccade was detected at the expected timing.
2. Subject forgot (or took too much time) to make a saccade just after the target switch.
3. Subject took too much time to give his answer after stimulus display.
4. Technical problem prevented a correct eye tracking resulting in no stimulus display (rare case).

Second we re-scaled all saccade movement on the range $[0, 20]^\circ$ and in the direction from 0 to 20°instead of having to deal with different saccade direction i.e. from -10° to 10° and from 10° to -10°.

Third we aligned each saccade movement on a common reference point i.e. we align the maximum velocity on 200 ms and we considered an analysis window for each saccade movement from 0 ms to 300 ms. We will thus consider for the further analyses the sampled eye position 200 ms before its maximum velocity and 100 ms after. The results of the second and third step on a few example saccades are visible on figure 2.4



(a) (b)

Figure 2.4: Example of results after second and third step

We can also specify that the velocity for the example above and for our further analysis had been computed following a simple central numerical derivative of second order:

$$v(t_i) \approx \frac{x(t_i + h) - x(t_i - h)}{2h}$$

with h being our step time i.e. 1 ms.

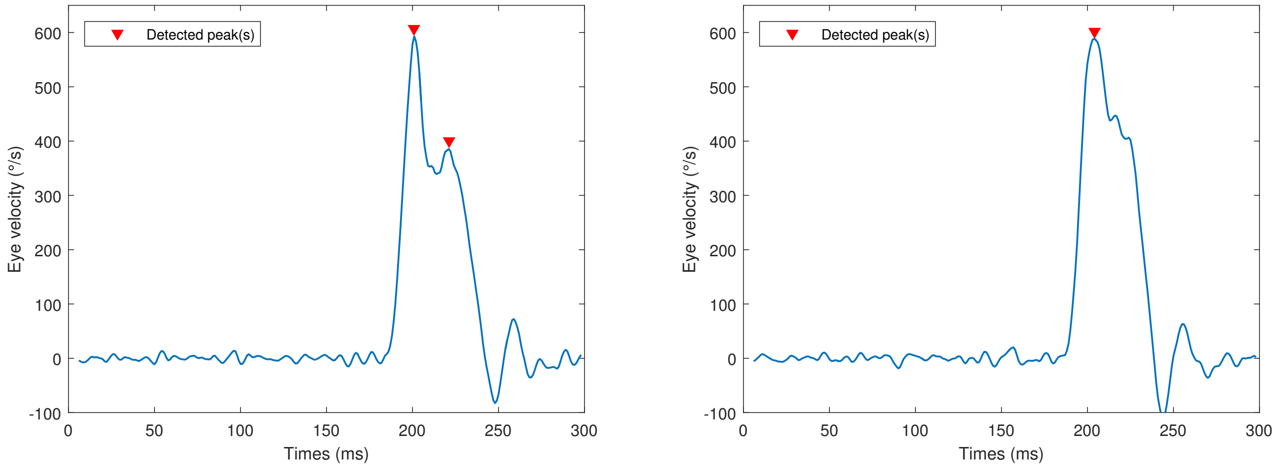
Fourth, we also operated a calibration offline to correct the small errors which could remain despite numerous online calibrations on the Eyelink. To do so data from calibration task preceding each detection task were used. Few points from the eye fixation timings were selected and then compared to the corresponding target position. Correction coefficients were then determined through least squares optimisation of $A \cdot x = b$ where A is the position target and b is the eye position.

Fifth for some analyses we filtered our curves. To do so we used a bi-directional low-pass auto-regressive filter at 47.6Hz. We will mention it when filtered data instead of raw data will be used.

2.2.6 Velocity analysis tools

For the further velocity analysis we decided to proceed in 2 different ways. First we observed during extraction of our data that there were something uncommon in the velocity peaks. Our first way to analyse velocity profiles is thus peaks detection: we want to detect the number of peaks in the main velocity sequence and quantify their presence in our dataset. Secondly we want also to extract the symmetry of the curve to analyse the conformity of the velocity profile shape from what is commonly observed.

For the peak detection we used the *findpeaks* Matlab function which allows to retrieve the local maxima of a curve. This function accepts several parameters to only keep the maxima which really interest us. Among these parameters the minimum peak height was set to $145°/s$ to avoid detecting the possible peaks after the main sequence; the minimum peak separation was set to 12ms to avoid detecting some artefacts on the first principal peak; and the minimum peak prominence was set to $10°/s$ also to discard noise and artefacts. Some examples are given on figure 2.5. The detection is quite restrictive as it can be observed on the right figure 2.5b where there is one only peak detected. Nevertheless the figure still show an asymmetry that will be taken into account with the second tool.



(a) Double peaks detected (b) Only one peak detected

Figure 2.5: Examples of peak detection

For the curve symmetry analysis we will simply define a symmetry index. This index is defined as the following ratio (see figure 2.6):

$$\frac{t_{peak} - t_{start}}{t_{end} - t_{start}}$$

This corresponds to the ratio of length attributed to the pre-peak part of the curve. A perfectly symmetrical curve will thus have an index=0.5. However this index requires a sufficient precision for the start and end timings of the saccade. These timings are particularly difficult to find in a reliable way if there is too much noise. This is why we will only use the symmetry index on filtered curves by doing so the details such as the second peaks will be "erased" but part of the asymmetry will nevertheless be conserved.

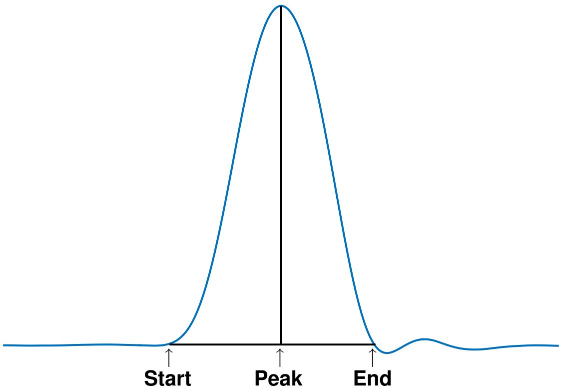


Figure 2.6: Representation of the curve symmetry

Chapter 3

Results

In this section we will show the results from our experience. We intend to highlight significant results as well as uncommon observations we made. This section is mainly organized around 3 axes: score detection evolution, saccade amplitude and velocity profiles. These are the main elements that attired our attention, we will try to understand if they are linked. Further explanations will be given in the discussion chapter.

3.1 Score detection analysis

3.1.1 Comparison between saccade block and no saccade block

We will thus first analyse the scores for the 2 parts of our experiment. For the first part we compare the detection scores of the "no saccade block" and the detection score of the first "saccade block". The purpose here was to verify that saccadic suppression makes the task much harder. The scores are visible on figure 3.1.

We previously stated that we expected the score for the no saccade block to be quite high. Here, the lowest score is 85% and there are only 3 below 90%. The mean score is 95.27%, thus globally we are in the range of expected score for this part and the task seems quite trivial for most of the subjects.

For the scores of first saccade block the maximum is 65.3% and the minimum 37.3%. Most of them are also quite distant from 33% score which is the expected score if subjects respond randomly for each trial. Consequently, subjects seem to show they still have sufficient perception during some saccade movements to achieve a global score better than random. Considering there are 6 people above the 50% upper threshold and mean is at 51.3% it seems we have a block a bit easier than what was initially thought, nevertheless there is still a highly significant difference between the two score distributions showing that the saccade block is a much more difficult task than the no saccade block due to saccadic suppression. We have thus showed eye saccade movement makes the detection task much more difficult but not impossible and that scores indicate subjects still have some perception during saccade to allow to detect a few stimuli.

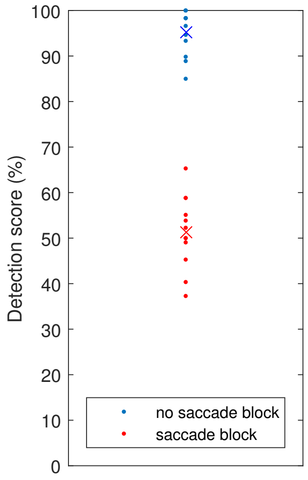


Figure 3.1: Subject's score for the first step. The dots represent subject's score. The crosses represent the mean score of each block.

3.1.2 Score evolution for all saccade blocks

For the second step the purpose was to see how the subjects will adapt from block to block facing this not so easy detection task. The purpose of so many repetitions of the task was to let them learn the task and allow subjects to increase the weight of the feedback from block to block. Indeed we supposed it will not be easy for them during the first trials to well focus on detection task and consequently the feedback weight could not increase as wanted. We hoped seeing them improve their detection score from blocks to blocks as it could be a first sign that weight of sensory feedback increase too. To analyse this we have plotted the evolution of detection score from block to block on figure 3.2.

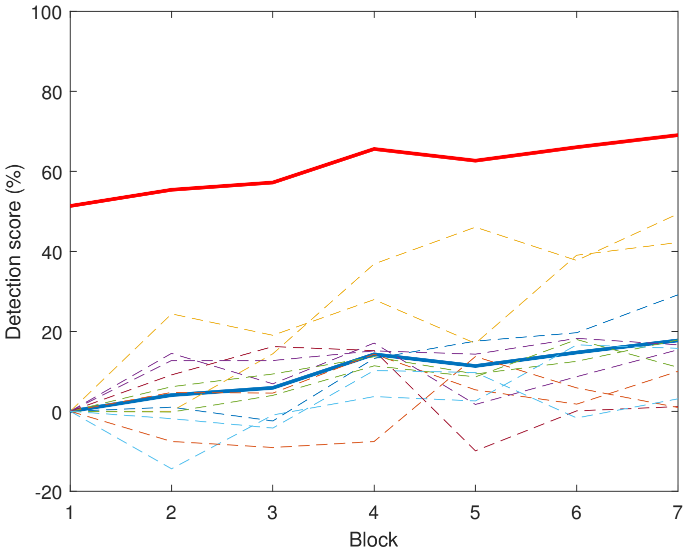


Figure 3.2: Detection score for each saccade block. Red solid line is the mean score evolution. Blue line is the mean score evolution relative to the score obtained for the first saccade block. Dashed lines is the relative score evolution for each subject.

We directly observe the smooth mean score amelioration (almost linear). The mean score for the last block (which is 69.1%) indicates subjects have enough information to detect most of the orientation which contrasts with the score for the first block of 51.3%. If we have a look a relative scores evolution for each subject we see that although some show bad performance during the first blocks the most of them tend to improve their score. At the end of the 7th block no one has regress and 9 out of 12 subjects show a score amelioration equal or above 10%. Moreover when looking at the relative mean score amelioration we observe that between the first and last block subjects have on average increased their score by 17.7%. When using a paired-sample t-test to statistically compare scores distribution for first and last block we obtain t_{11}=-3.98, $p - value$ = 0.002 meaning that the difference in scores distribution are statistically significant. We have therefore achieved to obtain a learning effect in most subjects.

3.2 Amplitude and error analysis

A result that caught our attention when data was extracted is the saccade amplitude. We will analyse these amplitudes and try to contextualise these results according our task and our goals. On figure 3.3 we can observe amplitudes for a subject through each saccade blocks. Since the first block the amplitude distribution is quite uncommon and it seems its amplitude variance is quite high even if we consider saccades in a same block. Moreover the fact that lot of saccades does not reach an amplitude close to 20 ° is very intriguing.

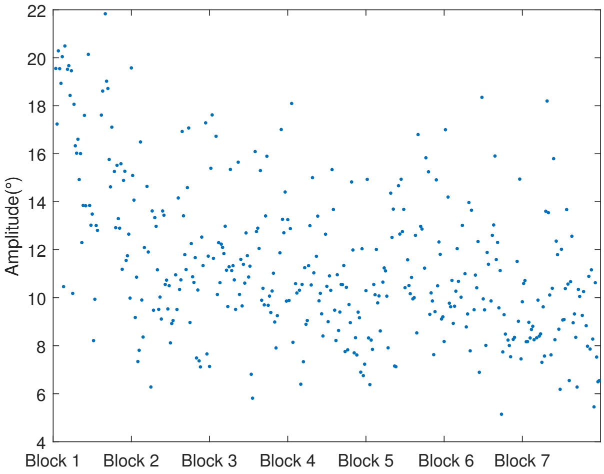


Figure 3.3: Saccades amplitude through each blocks for a particular subject.

It is known for this age range (20-25 years old) and for this saccade amplitude that we can expect a mean saccade undershoot of about 10% for this kind of task (i.e subjects make most of the time 18° saccade instead of 20°) [6]. However here it seems lots of saccade amplitude are much smaller than 18°.

For more convenience we will now talk about the saccade error i.e simply the difference between 20° and their saccade amplitude (consequently, a negative error means subject overshoot the target). If we compare the errors subjects made during their detection task and the errors for their calibration task we observe low saccade errors for the calibration contrasting with the high and strongly variable errors for the detection. This comportment seems to be present for most subjects [1].

When having a closer look at the first element that intrigued us i.e the amplitude variance on figure 3.5 we observe, except a weak decrease for the 3 first blocks, it is quite constant through the other blocks. Thus most of the subjects have a non-negligible variance quite constant through each block even if we can also notice there is one subject who have a quite low variance in comparison of the other (this is subject 7, red curve in the bottom). We could have imagined this variance to greatly reduce across the blocks as subjects got used to the task. As we have seen, this is not the case and this element seems rather constant.

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[1] Error graphs for all the other subject are visible at appendix .2

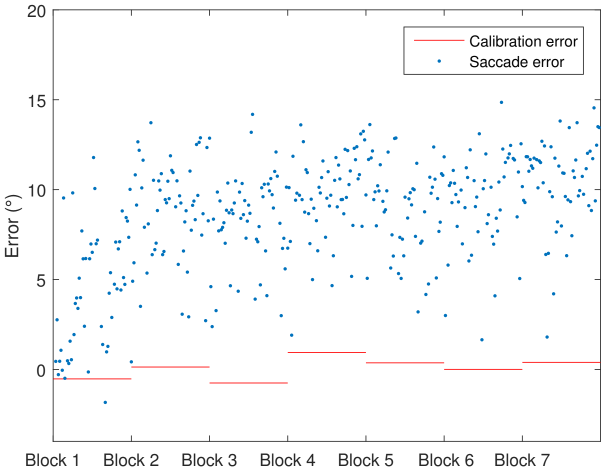


Figure 3.4: Comparison between error for each detection saccades and calibration saccades of each blocks for a particular subject.

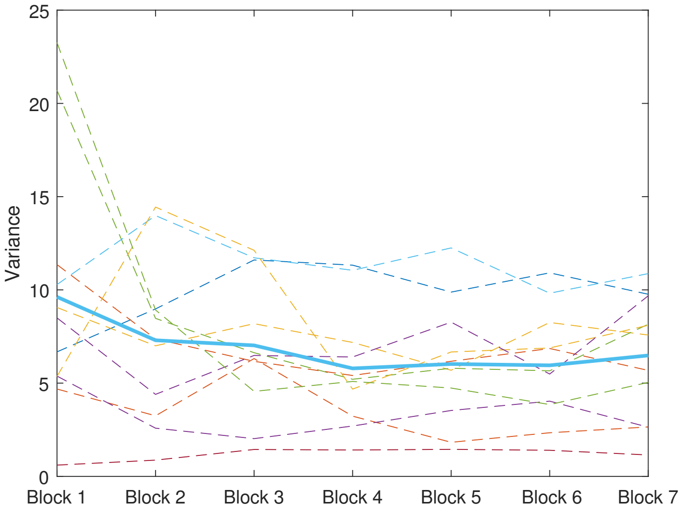


Figure 3.5: Variance through each blocks. Dashed lines are subjects variance; Solid line is the mean on each subjects

Another observed effect on figure 3.4 is despite variance does not seems to strongly change, mean amplitude error seems to progressively increases. We have summarised the mean error on each subjects for bin of 20 saccades on figure 3.6. The influence of the detection seems quite visible. First comparing the error for calibration task with the error for the detection we clearly see a gap. For the calibration results we have to remember the data are corrected through projection of the calibration saccades on 20° amplitude (this correction is however most of the time quite minim since there also were online calibrations on Eyelink device). This explains the very low mean error (-0.3°, which is still smaller than the diameter of the target) for this case. Consequently the gap between calibration and the first bin does not seem abnormal, indeed as said previously for saccades of 20 ° it is still common to observe a 10 % undershoot [6]. However the mean error progressively rises until reaching almost 7° for the 20 last saccades of our experiment which is now far away from it usually is observed for this age range.

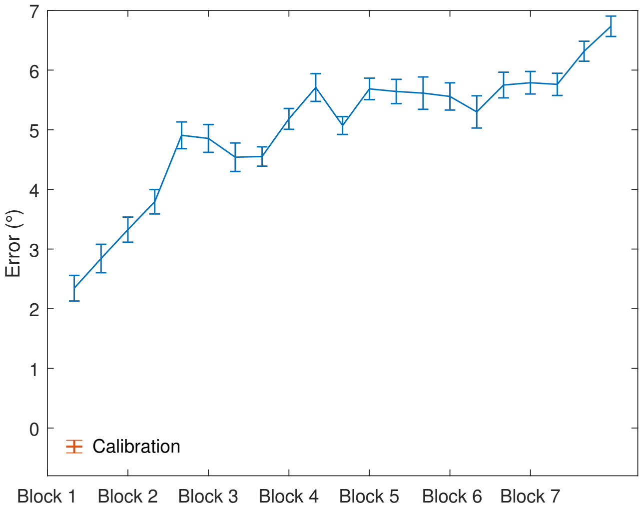


Figure 3.6: mean±(SE) amplitude error through each blocks.

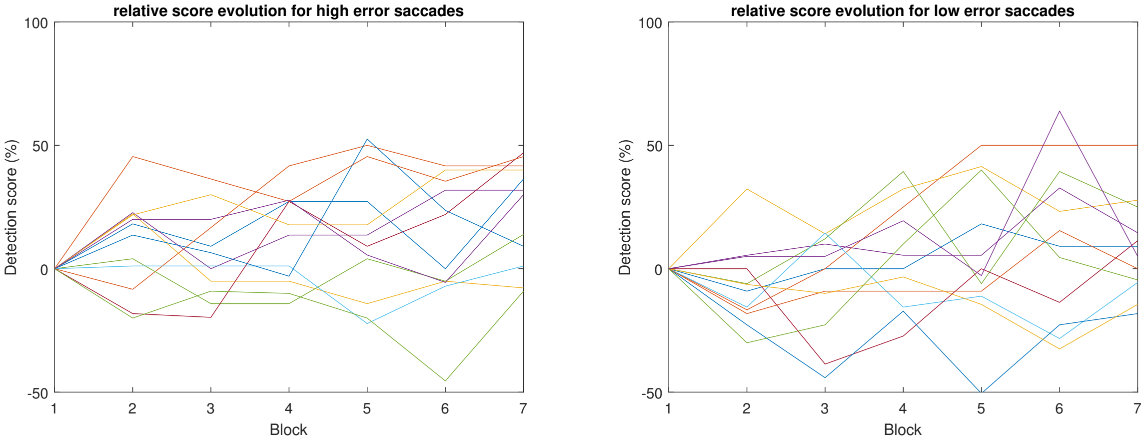
From our observations about score evolution and error evolution it appears they both tend to increase through the blocks. It is assumed that subjects tend to focus their attention on the stimulus rather than the fixation target. Consequently it seems to be competition between the task of discriminating the stimulus and the task of programming the saccade. This seems consistent with studies of the direction of attention during saccade [2][8] that tend to show that the discrimination of a stimulus is the best when the end point of the saccade is situated on the stimulus. Moreover it is highlighted that it is difficult to direct the attention to a place different from that of the target of saccade even if they are very close. Consequently, it is clear that there is a gradual orientation of saccades towards the place where there is the best chance of discriminating the stimulus. This seems to be confirmed by the fact that it has been observed that the score seems to increase according the amplitude error. Knowing that the stimulus was centered at 0° (i.e after a travelled distance of 10 °) it seems normal to see subjects gradually converge their saccades towards this value. The variance in saccade amplitude could be due to the fact that as can be seen in the figure 2.3 the stimulus covers a large part of the area between the 2 targets even though it is wider and sharper on the center. Therefore, subjects do not necessarily need to stop precisely at 0 ° but can stop in an area wide enough to allow them to even easily perceive the stimulus.

3.3 Second analysis of the score

3.3.1 Comparison between high saccade error and low saccade error

Here we will again have a look a the scores since we have seen that error and score seems both to increase through the blocks. We can verify that score is effectively dependent from error in our conditions. We have seen that for most subjects there already are high error saccades in the first block, thus we decided to analyse in a way a bit different the scores. We took the percentiles of our error data and we created 2 different groups: one for high error saccades i.e saccades where error was above the 80th error percentile; one another for low error saccades i.e saccades where error was below the 20th error percentile. By doing so we conserve for the 2 groups on average 11 saccades per blocks and per subjects.

We can first have a look at each subjects relative score evolution in the 2 groups (see figure 3.7). Despite some variance in score evolution of each subjects (surely due to restricted amount of saccades) we can still notice that evolution for the last block seems globally a bit better for the high error group. Moreover there are only 4 subjects for which the score improvement is below 10% for high error group while there are 7 (almost 8) subjects for the other group. This is a first element which seems in agreement with our assumption.



(a) (b)

Figure 3.7: Score evolution relative to block 1 for each subjects in both groups

We can then plot the mean score evolution through each blocks for both groups (see figure 3.8) to try to observe a more evident effect of the amplitude error. On this graph we clearly observe an important gap of at least 15% score detection between the 2 errors group. Moreover the score evolution between the first and last block is +20.29% for high error saccades whereas it is a bit lesser for low error saccades i.e +8.34%. When performing t-test for the evolution between first and last block of each groups we got $t_{11} = -3.88$, $p - value = 0.002$ for high error group and $t_{11} = -1.49$, $p - value = 0.163$ for the low error group. The score evolution is thus significant for high error saccades whereas it is not for low error saccades. Following these results is seems that saccade error had a non negligible impact on the score of our detection task, the positive score evolution is thus mainly due to high error saccade.

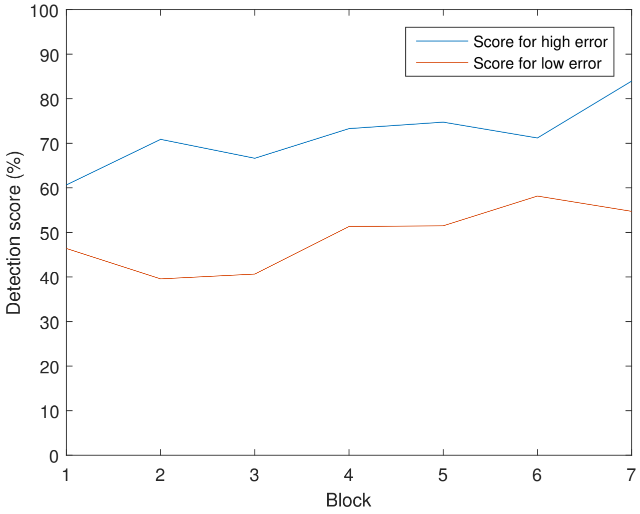
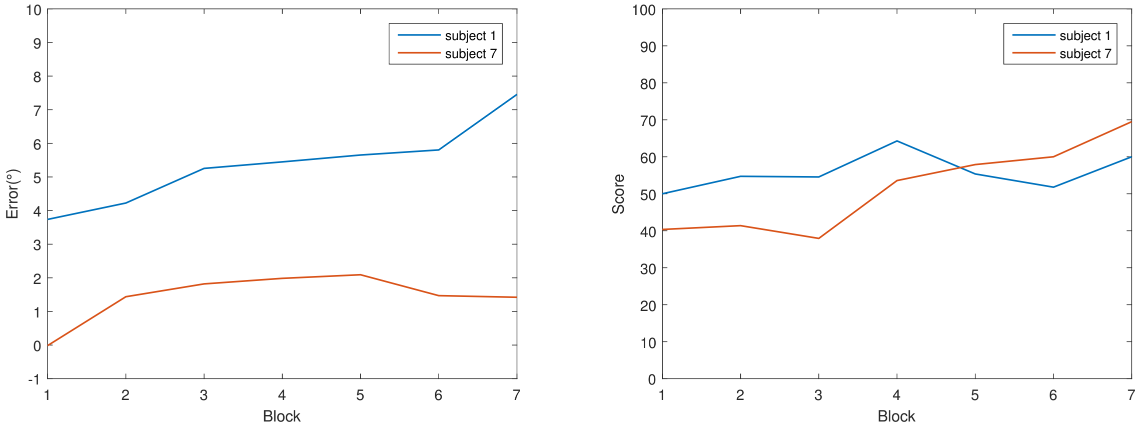


Figure 3.8: mean score through blocks for high error saccades and low error saccades.

Nevertheless this is a global view and counter-examples among a few subjects exist. We previously noticed that subject 7 shows a particularly low amplitude variance and low mean error in comparison of other subjects. We can have a look at its score on figure 3.9b where it is compared with a subject that shows an high variance and an high mean error (subject 1). We can see that despite most of its saccades showed low error, its score improve greatly: $+\sim 30\%$ of correct detection. In comparison, subject 1 showed an important mean error that strongly increased through the blocks but its score improved less: $+\sim 10\%$ of correct detection. Therefore although saccades error and score both increased through blocks, it seems that a strong increase of error is not a necessary condition to improve detection performance: score can still greatly improve even with lower increase of error.



(a) Error comparison

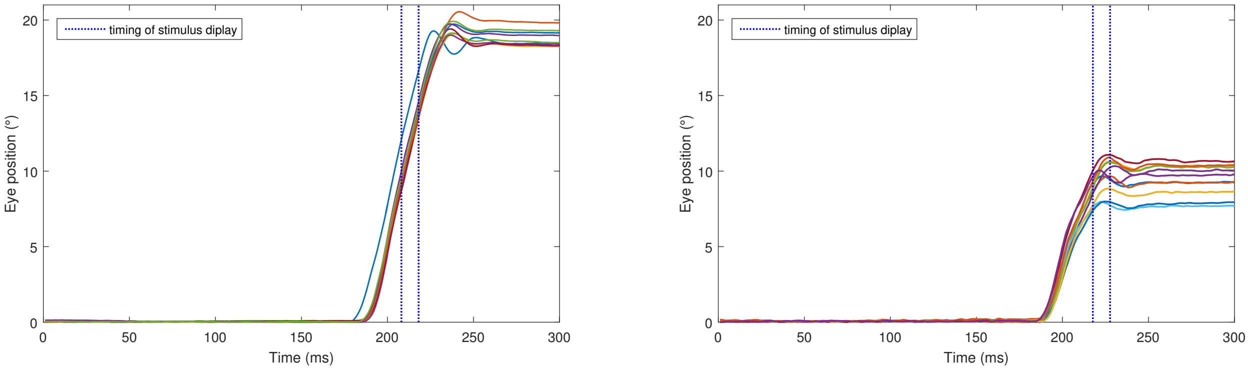
(b) Score comparison

Figure 3.9: Comparison of 2 subjects

3.3.2 Effect of the display timing and saccade amplitude

It has been shown in the preceding sections that the saccade amplitudes were rather variable and that an important proportion of them were situated around 10°. These saccades were logically later found in our high error group and we showed that the scores and their evolution were much higher for these saccades presenting a high error. However, as indicated in the methods section, according to our timing constraints the stimulus can be flashed only on average 40 ms after the beginning of the saccade. It is therefore legitimate to ask whether for these shorter saccades the stimulus would not be flashed a bit too late which might be responsible for improving the detection scores. This is what we will see here.

If we look at the timing of display of the stimulus for the low error group on the figure 3.10a we see that it is flashed as hoped during saccade. On the other hand, when we look at the figure 3.10b for the high error group we see that it also corresponds approximately to 40ms but due to the reduced duration of the saccade the stimulus is flashed relatively late and appears on the subject on the very end of his saccade.



(a) Low error group

(b) High error

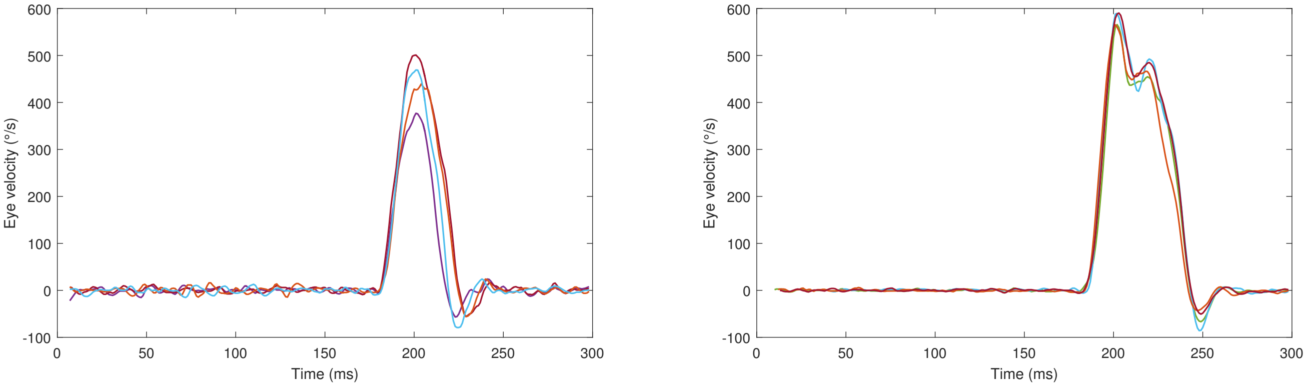
Figure 3.10: Mean timing of display for both groups according a block of a subject. The dashed vertical blue lines correspond to the mean starting and ending stimuli timings

Nevertheless as already explained before, saccadic suppression still occurs after saccade movement and for 10° saccades 40ms after the saccade onset, the magnitude of saccadic suppression is still close to its maximum [5]. Therefore we believe that display timing did not play a major role for the detection task.

However we have to take another element into account when dealing with magnitude of saccadic suppression: the amplitude. Indeed it has been showed that saccade amplitude affects the magnitude of saccadic suppression. W.H. Ridder and A. Tolimson [13] showed that the saccadic suppression magnitude was lower for 10° or less saccades than for 20° saccades. It is thus quite sure that this element plays a role in the score enhancement for higher amplitude errors.

3.4 Velocity analysis

We have already observed two parameters whose behaviour appeared uncommon to us: first the score enhancement through blocks as well as the high variance and the high saccade errors. We now turn to the control of movement more specifically by analysing the velocity traces. A way to proceed is to analyse the velocity profiles of the saccades. If movement trajectories are affected by an high sensory feedback weight we should see a clear impact on the velocity profiles whereas the impact on eye position profile could be less evident.
According to literature the typical main sequence for 10° to 20° saccade amplitudes is a symmetrical bell curve whose maximum velocity is approximately between $400°/s$ and $500°/s$ (depending on the amplitude)[4]. We have plotted on figure 3.11 some examples of the profiles we got. From all the profiles we saw during our analysis we can show two main trends: first there are classical velocity profiles with small common artefacts (which surely come from the noise at the recording); second velocity profiles with a first sharp peak follow by a second smaller peak (and sometimes also by a third peak). We will analyse these profiles with the 2 tools we previously presented.



(a) Common velocity profiles

(b) Uncommon velocity profiles

Figure 3.11: Examples of observed velocity profiles

3.4.1 Double peaks analysis

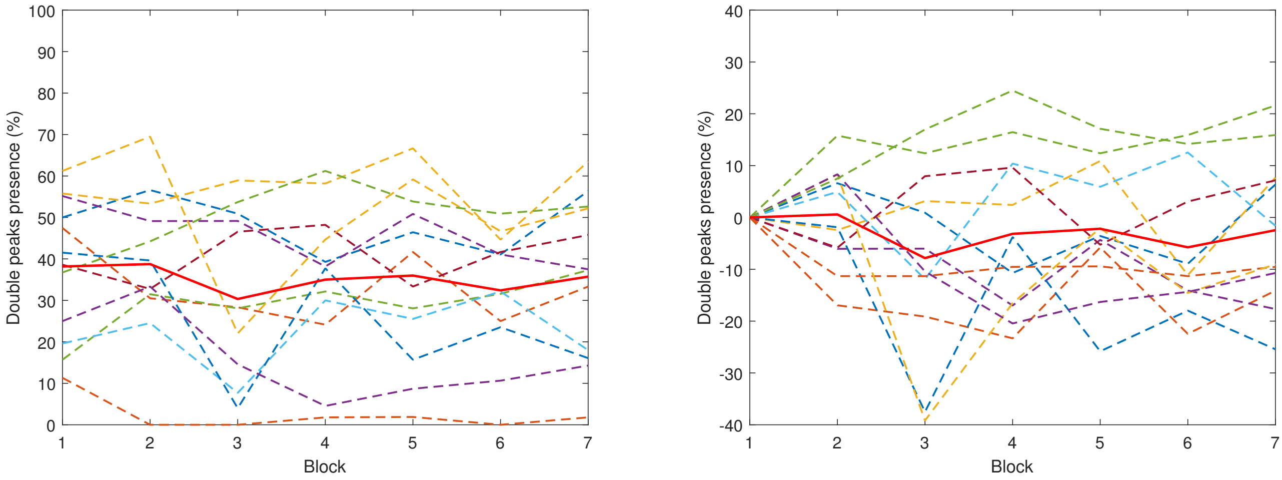
First, we want trying to quantify the amount of double peaks profiles amongst all our saccades. As previously showed the peak detection is quite restrictive to avoid false positive. Nevertheless, it will give us a low boundary estimation of double peaks presence.

Double peaks velocity profile is an extremely unusual behaviour when talking about simple horizontal eye saccade. Unusual velocity profiles of this kind can be observed for 2D task where eye operate smooth pursuit and then suddenly eye saccade [11]. However here it is clear that we are not in conditions where subjects operate smooth pursuit movement which confirm the unusual nature of these profiles.

We will thus try to quantify the presence of these uncommon velocity profiles as well as their impact on the detection task. Concerning their presence through blocks these double peaks are present for 34% of all the saccades and as we can see on figure 3.12b this presence is quite constant. The evolution of presence relative to block 1 among subjects seems quite spread but on average it does not strongly deviates from 0%. However on figure 3.12a we also observe that double peaks presence is quite variable between subjects. Some subjects have up to 50% where others are closer to 20% and 1 subject (subject 9) has almost none for each blocks. Anyway this gives us a first essential information: there are velocity anomalies since block 1 for almost all subjects.

We can also make the comparison with our calibration saccades preceding each blocks. At first view 21.4% presence of double peak saccade among them. However, we had to correct some elements, by inspecting these saccades we noticed subject 10 did not realised ideal -10° to +10° saccades, instead he did many small jumps between these 2 targets. Indeed the instruction was they have to fixate the different calibration targets when they appeared, we did not precise they have to make eye saccade to reach them because that seemed to us the most logical behaviour. Anyway he is the only one that did not realised its calibration task with nice one-shot saccades. When discarding subject 10 results we got double peak presence of 19.4%. This means the double peak presence is still quite high among these calibration saccades. This high presence value is in part due to subject 7 which surprisingly present for all its 7 calibration saccades a double peak.

This is thus another surprising fact, although it seems that calibration saccades on average present less double peak than for detection saccades, this presence is not close to 0. Indeed we expected anomalies presence for calibration to be very small, since subjects does not have to detect stimulus during their saccades. In these conditions feedback weight should be close to its regular value during saccade and so the velocity profile.



(a) Presence of double peaks

(b) relative evolution of the presence of double peaks

Figure 3.12: Double peaks evolution through blocks

Concerning the score evolution for double peaks curves, we observe on figure 3.13 the scores for both groups. Here it seems that there is no strong score difference through block for both groups: no gap between the 2 scores curves nor difference in the slope of their curves. The mean score for double peaks groups is 60.40% and is 61.39% for the unique peak group. Which seems to indicate that there would be no dependence between velocity anomalies and score.

Concerning the saccade error, here on figure 3.14 we do not observe a difference in the "slope" curves but it seems there is a small gap of approximately 1.5° between the 2 groups.

We can also have a look at the proportion in "high error" and "low error" groups we used previously. The proportion of saccades with a second peak is 29.9% in the high error group whereas it is 47.5% in the low error group which is consistent with the figure 3.14 and suggest that saccades with second peak have a lower error. If we perform a ttest between the 2 peaks groups on the error of each subjects for the last block, we obtain $t_{11} = -3.10$, $p - value = 0.01$ meaning that the difference in error between the 2 groups is significant for the last block. Since the mean difference for each blocks is quite the same it seems that error is globally significantly higher for curves without double peak. It is quite intriguing since according to the global results saccade error and score seemed to be linked but here double peaks could have an impact on error but not on score. We will see if the tendency is the same for our second velocity analysis.

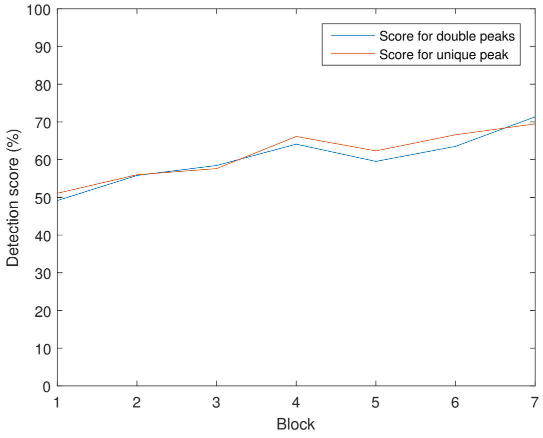


Figure 3.13: Score evolution for double peaks and unique peak

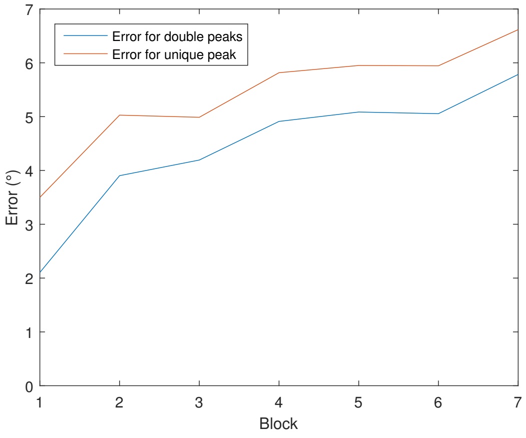
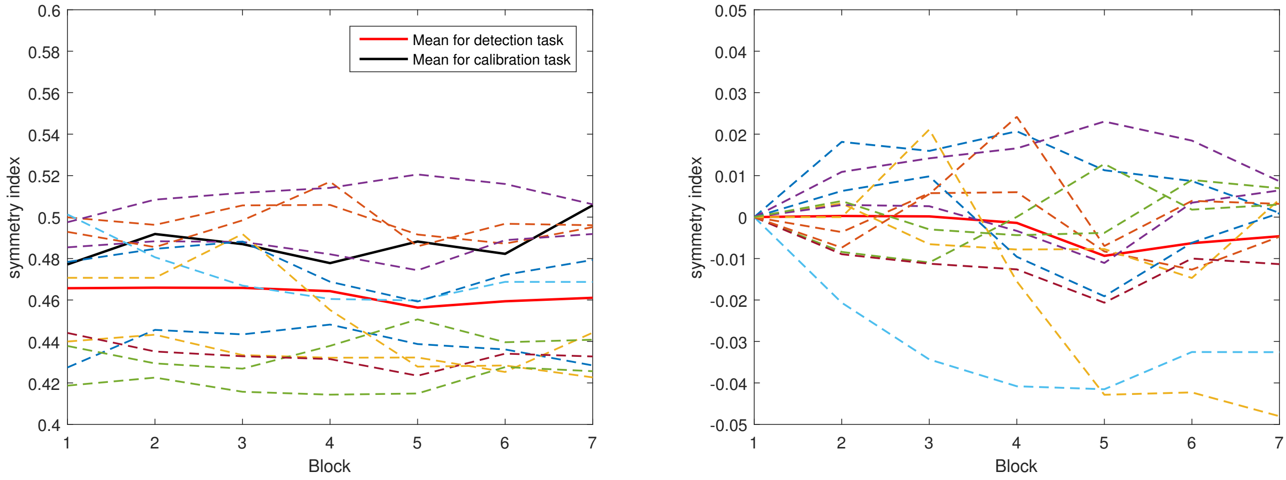


Figure 3.14: Error evolution for double peaks and unique peak

3.4.2 Asymmetry analysis

For the second velocity analysis we will use the curves symmetry index. When we considered double peaks we knew that we were obviously considering a lower estimation of the unusual amount of velocity profiles since the detection is quite restrictive and the unusual curves does not all have a clear second peak. Here for the asymmetry analysis all asymmetry will be taken into account but since curves are filtered this asymmetry may be a bit underestimate. This second analysis is intended to verify that conclusion on analysed elements match when considering another approach.

First of all if we have a look at the symmetry index for all subjects on figure 3.15a, we can see that most of subjects have an index below 0.5, meaning that on average their velocity profiles are shorter for the pre-peak part than the post-peak. Only 4 of them have a symmetry index close to 0.5 through each blocks. The mean index through blocks is quite constant, for the last block it is at 0.46. If we have a look at the relative evolution (evolution in comparison of block 1) on figure 3.15b, the distribution is less dispersed and a bit more constant than what we had observed for the double peak distribution. However, we can still note the strong index decrease



(a) Symmetry index for all subjects through blocks; Dashed lines are subjects symmetry indices for detection task

(b) relative evolution of the symmetry index for detection task

Figure 3.15: Symmetry index evolution through blocks

for 2 of them (blue and yellow curves in the bottom; subject 6 and 10), the same trends has not been observed on figure3.12b. Concerning the subject which has almost none double peak (subject 9), here its symmetry index is also very close to 0.5 and its mean indices never goes below 0.485. This is a first common point with peak analysis, it also appears here that we have most of subjects who presents many uncommon velocity profiles since block 1 and that velocity anomalies is quite constant through blocks.
We can also compare indices from detection task with indices from calibration task. By again discarding saccades from subject 10 we get a mean symmetry index of 0.487. The detailed values for blocks are on figure 3.15a in black, we clearly see the gap between the calibration and detection task indicating that calibration saccades are on average less disrupted. Since we also have showed there were double peaks for calibration saccades, it seems normal to observe a mean symmetry index still a bit below 0.5.

As for peak analysis we will continue by observing what happens for score and error. To do so we decided to make 2 groups the first one will be the "low asymmetry" group and will represents all the saccades that show an index greater or equal to 0.485; the second group will be the "high asymmetry" group and will contain all the saccades with an index lower or equal to 0.46. By doing so we get 35.9% of all saccades in the low asymmetry group and 48.1% in the high asymmetry group, the rest of the saccades are between 0.46 and 0.485 or are discarded saccades (see Data post-processing section in Materials and methods chapter).

For the score evolution on figure 3.16 we again observe very small differences between both groups, there is no clear gap between curves and slope are quiet identical. The means score for low asymmetry group is 62.50% and for high asymmetry group it is 60.94%. This is in agreement with what we observed previously for peak analysis: velocity anomalies do not seem to have an impact on score detection.

For the error evolution on figure 3.17 we can observed that the high asymmetry group is on average a bit higher than the low asymmetry group except for the 6th block. As for the peak analysis we can also have a look at the low error and high error groups. For the high error group the mean symmetry index is 0.465 and for low error group it is 0.458. These values are quite close of the mean observed on figure 3.15a which indicate that curves for both groups are on

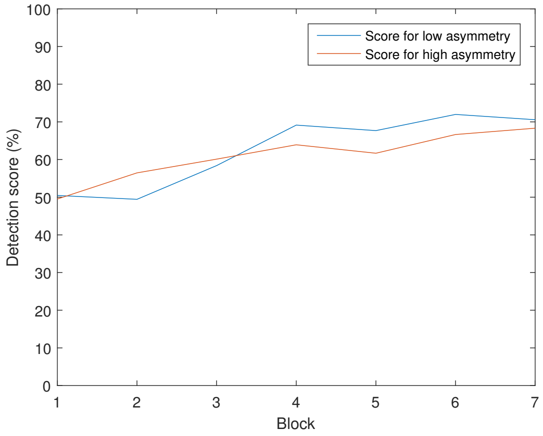


Figure 3.16: Score evolution for low and high asymmetry

average quite asymmetric with no big difference between them. The results of the figure 3.17 is globally in opposition to what was observed for the peak analysis and for symmetry index of both error groups which tend to show that error is a bit higher for curves with no big velocity anomalies. Nevertheless, the differences on figure 3.17 are lower than 1 ° for each blocks.

From what we can observed for this comparison it seems there is no big influence of the velocity anomalies on the error. Starting from the fact that our 2 analyses for the score tend to show that there is no link between velocity anomaly and score, it seems logical that there is none for the error either (since we previously showed that error and score seems to be linked).

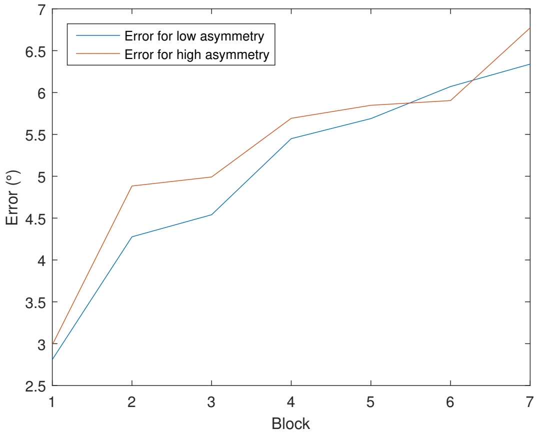


Figure 3.17: Error evolution for low and high asymmetry

Finally we can also talk a bit about subject 9, this is the only one who shows almost no anomalies through all its blocks. However we did not observe other uncommon thing about it. The only element that can be highlighted is that it is the subject with the highest average score, the one with the highest pay of all. However this score is also not excessively higher than the others and does not appear to us abnormal. For example subject 2 [2] has also good results with a very good improvement of its score however it shows many saccades with velocity anomalies.

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[2] Detailed score are visible at appendix .1

From these observations, it seems that unusual velocity anomalies are significantly present in our dataset, which at first sight seems consistent with what Crevecoeur and Kording's hypothesis predicted. Regarding the link between these anomalies the score and the error this is less evident. Both velocity analyses seem to show that there is no link between these anomalies and the score. However for the error our first analysis seems to show that error is significantly higher for curves without anomalies whereas it is not the case for our second analysis.
It is also intriguing to observe some velocity anomalies for the calibration task whereas there is no apparent reason especially with subject 7 which presents these anomalies for all its calibration saccades (recall these anomalies are extremely atypical and could not be there simply by chance).

Chapter 4

Discussion and conclusion

As we had announced, in the previous part we worked around 3 important elements: the score, the error and the velocity profile. We observed for each their evolution through the different blocks of saccades and checked the links between them. We will review and discuss some points that may explained what we observed. Finally we will finish by looking at what these results allow us to conclude about origin of saccadic suppression.

First of all for the score, the initial idea was if we saw an increase of the score then the subjects gained in perception and thus it was probable that it could be an element indicating an increase of feedback weight through the blocks. We showed that the subjects improved from block to block and that a learning effect was obtained.
Crevecoeur and Kording's hypothesis indicates if the weight progressively increases then more and more unusual saccades should emerge from our data. As a reminder the main sequence corresponds to the characteristic bell-shaped profile of the eye velocity. Here the double peaks and the asymmetry observed for lot of profiles in our data highlight a disruption of the main sequence. However, we have seen that firstly the number of saccade with double peaks did not increase so that the effect was not on average more present through blocks, secondly that the asymmetry of the saccades did not increase so that the disruptive effect did not seem stronger. 34% of the saccades showed more than one velocity peak and 48.1% was in the high asymmetry group, knowing these values were constant through the blocks, this seems to indicate there was indeed a large number of saccades whose main sequence have been heavily modified.

If we also take into account that these values were already reached for the first block, then it appears that there has been no progressive increase in weight but that a maximum value related to the framework of this experiment was rapidly reached. The gradual increase of the score therefore does not seem to be due to a progressive increase in the feedback weight but rather to another element that can influence the perception.

Since it has been shown that the score and the error seem to be related, this element could very well be the mechanism of attention we have already spoken a little earlier. It is known that the discrimination of a stimulus is quite bad if the ending point of the saccade and the position of the stimulus are different. Thus, there is a conflict between the instruction to perform a 20° saccade, and the instruction to perceive the stimulus flashed in the middle away from the goal target. This conflict could be the cause of the gradual saccade shortening among subject i.e the attention mechanism could take more and more priority over the realisation of a 20 ° saccade which results in an higher error. This reduction of amplitude would facilitate their point of attention but also as we saw it would decrease the intensity of the saccadic suppression. These 2 elements appear us as very likely responsible for the score and error increase. The priority of the attention could also explain the variance in the saccade amplitude. Indeed, since the stimulus is very wide there is not only one specific point where the perception is high, there are in fact many points that are valid to well perceive it resulting in a wide range of amplitude. Moreover as we said, for many subjects the average error seems to progressively increase, by taking into account that the center of the stimulus is the clearest and the most visible part, attention could especially be directed on it and we could see the mean saccade amplitude finally converge to it (i.e at $x = 0°$, so error $= \sim 10°$). To confirm this, it may be possible to redo the same experiment but with a significantly smaller stimulus but which can still be visible to the subjects. It would therefore be necessary to have the least possible latency between the display of the stimulus and the detection of the saccade to effectively estimate the eye position at the desired time and thus be able to display the stimulus in the center of the field of vision of the eye. If these assumptions are confirmed then we should see a clear decrease in the variance and see more clearly the error converged to a certain point.

Nevertheless, we also have to recall that despite score increase for low error saccades is not significant we have seen that subject 7, which has a very low mean error, had still great score enhancement. This could suggests that the error is not the only parameter that influences the score and consequently there could be another phenomenon to take into account.

One another intriguing element that we have seen is that despite the seemingly non negligible gap between calibration task and detection task for the presence of anomalies, there are still a few double peaks present in the calibration task (very similar to those observed for the detection task). This should not be the case, since we are not in a situation where the feedback weight should be higher than in regular conditions. Therefore, calibration saccades do not seem to be ideal references for comparison. One possible explanation is since we explained to the subjects that the main purpose was to detect the stimuli orientation before starting the experiment, subjects began to pay attention (and thus increase the feedback weight) before the beginning of the detection task i.e during the calibration task. To verify this and to have better references for comparison, it could have been interesting to integrate to the experiment a control block even before the no saccade block. For this control block, subjects should have just done 60 saccades of 20° without prior information about the following detection tasks. By doing so we could have verify that the anomalies were not due to experiment context or technical problem but really from the increase of feedback weight. Moreover it would have made a larger database for comparison than the 7*12 (minus those of subject 10) calibration saccades we got.

Whether the velocity anomalies influence the score or the error it is less clear. To try to quantify velocity anomalies we decided to use 2 different tools. As we have shown, these 2 tools seem to indicate that there is no link between velocity anomalies and score. We showed by taking as example the subject 2 and 9 that although their velocity profiles were totally different, their scores were not. Consequently, these anomalies do not seem to help or worsen perception.
With regard to the link with the error, we saw that the peak analysis seemed to indicate a statistical impact by showing that the anomalies could reduce the saccade error but the analysis of asymmetry could not confirm it. It is surprising that there may be a possible impact on the error but not on the score, since for the reasons mentioned above the error seems to have a positive impact on the score. Nevertheless, the figure 3.14 shows that the difference between the 2 groups is between 1° and 1.5°. It may therefore be possible that the gap is not sufficiently high to create a strong and visible influence on the intensity of the saccadic suppression and on the mechanism of attention. This is perhaps one of the weak points of our analysis, our 2 tools are quite convenient to quickly get an idea of the presence of uncommon velocity profiles, but they may lack precision to be able to go further in the analyses. As indicated, the weak point of the peak detection is that it is quite restrictive and that there could have been a significant proportion of double-peaked saccades found in the single-peak group, which may "dilute" information. As for the symmetry indexes, the fact that this requires a significant filtering of the data may reduce a bit too much the asymmetry and as for peak analysis group separation may be poorly perform.

To conclude on the one hand we have seen that attention mechanism seems to have played a well visible role on score and error evolution. This effect was also probably amplified by the modulation of saccadic suppression with saccade amplitude.
On the other hand our main goal was to be able to draw a conclusion about Crevecoeur and Kording's hypothesis, we showed there were lot of uncommon velocity profiles in our dataset which is consistent with what they had predicted i.e during saccade the more the feedback weight increases the less eye control is efficient. This is thus a main result of this work, this tends to validate the idea of a eye sensorimotor computation responsible of saccadic suppression and that there may be a cross talk between perception and control in the brain. However trying to quantify the impact of these anomalies on score and error was a bit more complicated. It seems that our tools lacked a bit of precision to go further in the analysis.
In addition of finding a more precise analysis method, for following experiments it would be interesting to integrate a control block as well as to reduce the size of the stimulus to check how it will impact the attention effect. These possible future analyses seem worth to us in the light of the very promising results obtained during this work.

Bibliography

[1] Frederic Crevecoeur and Konrad P Kording. Saccadic suppression as a perceptual consequence of efficient sensorimotor estimation. *eLife*, 6, 2017.

[2] Heiner Deubel and Werner X Schneider. Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision research*, 36(12):1827–1837, 1996.

[3] Mark R Diamond, John Ross, and Maria C Morrone. Extraretinal control of saccadic suppression. *Journal of Neuroscience*, 20(9):3449–3455, 2000.

[4] Christopher M Harris and Daniel M Wolpert. Signal-dependent noise determines motor planning. *Nature*, 394(6695):780, 1998.

[5] Michael Ibbotson and Bart Krekelberg. Visual perception and saccadic eye movements. *Current opinion in neurobiology*, 21(4):553–558, 2011.

[6] Elizabeth L Irving, Martin J Steinbach, Linda Lillakas, Raiju J Babu, and Natalie Hutchings. Horizontal saccade dynamics across the human life span. *Investigative ophthalmology & visual science*, 47(6):2478–2484, 2006.

[7] Mario Kleiner, David Brainard, Denis Pelli, Allen Ingling, Richard Murray, Christopher Broussard, et al. What's new in psychtoolbox-3. *Perception*, 36(14):1, 2007.

[8] Eileen Kowler, Eric Anderson, Barbara Dosher, and Erik Blaser. The role of attention in the programming of saccades. *Vision research*, 35(13):1897–1916, 1995.

[9] Bart Krekelberg. Saccadic suppression. *Current Biology*, 20(5):R228–R229, 2010.

[10] Jungah Lee and Choongkil Lee. Changes in orientation discrimination at the time of saccadic eye movements. *Vision research*, 48(21):2213–2223, 2008.

[11] Jean-Jacques Orban de Xivry and Philippe Lefevre. Saccades and pursuit: two outcomes of a single sensorimotor process. *The Journal of Physiology*, 584(1):11–23, 2007.

[12] D. Purves, D. Fitzpatrick, L.C. Katz, A.S. Lamantia, J.O. McNamara, S.M. Williams, and G.J. Augustine. *Neuroscience*. Sinauer Associates, 2001.

[13] William H Ridder II and Alan Tomlinson. A comparison of saccadic and blink suppression in normal observers. *Vision research*, 37(22):3171–3179, 1997.

[14] John Ross, M Concetta Morrone, Michael E Goldberg, and David C Burr. Changes in visual perception at the time of saccades. *Trends in neurosciences*, 24(2):113–121, 2001.

[15] Alexander Thiele, Peter Henning, M Kubischik, and K-P Hoffmann. Neural mechanisms of saccadic suppression. *Science*, 295(5564):2460–2462, 2002.

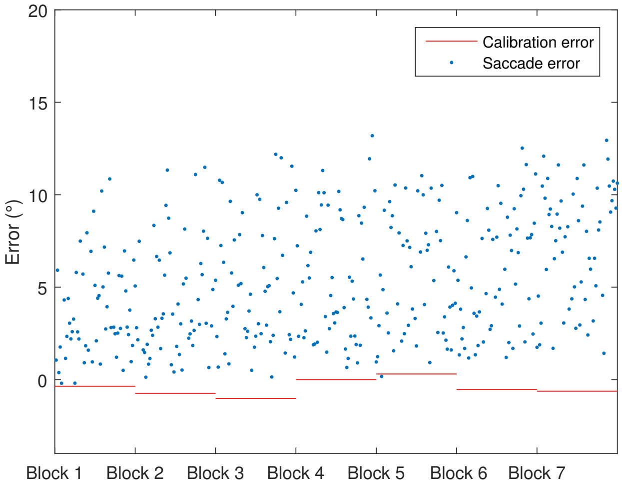
[16] Robert H Wurtz. Neuronal mechanisms of visual stability. *Vision research*, 48(20):2070–2089, 2008.

Appendices

.1 Detailed scores for saccade blocks

	Bloc 1	**Bloc 2**	**Bloc 3**	**Bloc 4**	**Bloc 5**	**Bloc 6**	**Bloc 7**
Subject 1	50	54.7	54.5	64.3	55.4	51.8	60
Subject 2	37.3	37.3	51.7	74.1	83.3	75.0	86.7
Subject 3	53.8	68.3	60.7	70.9	55.6	62.5	69.2
Subject 4	50.0	56.1	59.3	63.6	59.3	62.5	67.9
Subject 5	58.8	44.4	57.9	62.5	61.4	75.4	74.6
Subject 6	58.8	67.9	75.0	74.0	48.9	58.9	60
Subject 7	40.3	41.4	37.9	53.6	57.9	60.0	69.5
Subject 8	49.1	41.5	40.0	41.5	62.7	54.9	50.0
Subject 9	45.3	69.6	64.3	73.2	62.3	84.3	87.5
Subject 10	55.1	67.8	67.8	70.2	69.4	73.3	71.7
Subject 11	52.27	52.1	56.2	63.6	60.9	70.2	63.3
Subject 12	65.3	63.5	61.1	75.5	75.0	63.6	68.4

.2 Amplitude errors for all subjects



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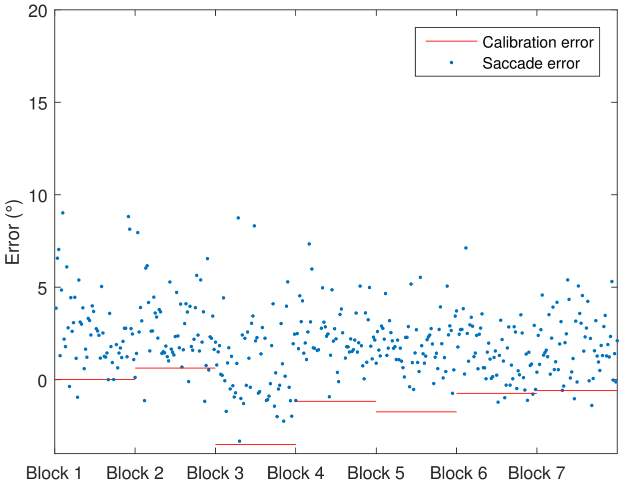

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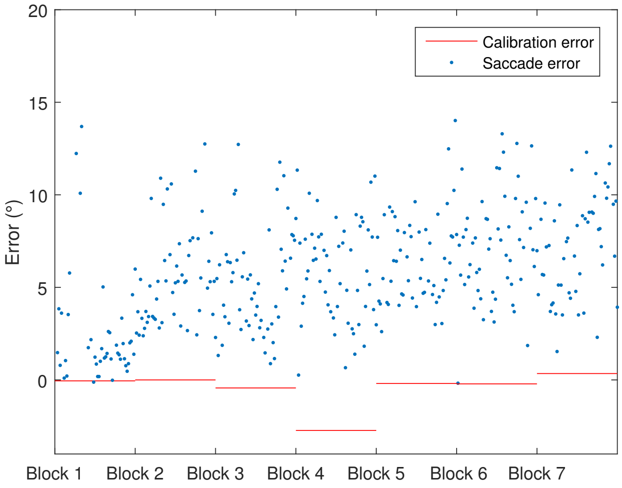

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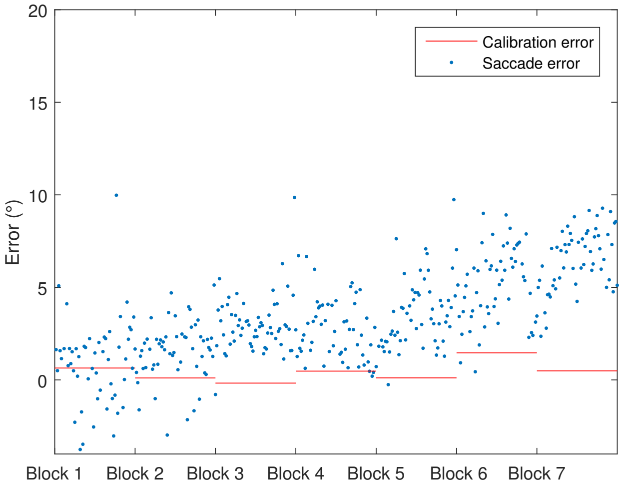

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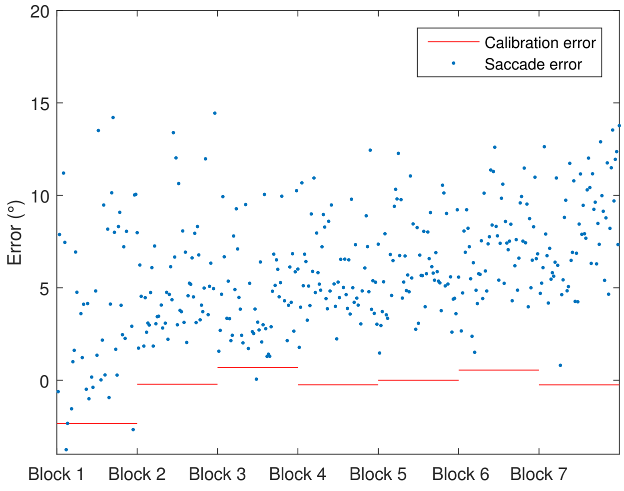

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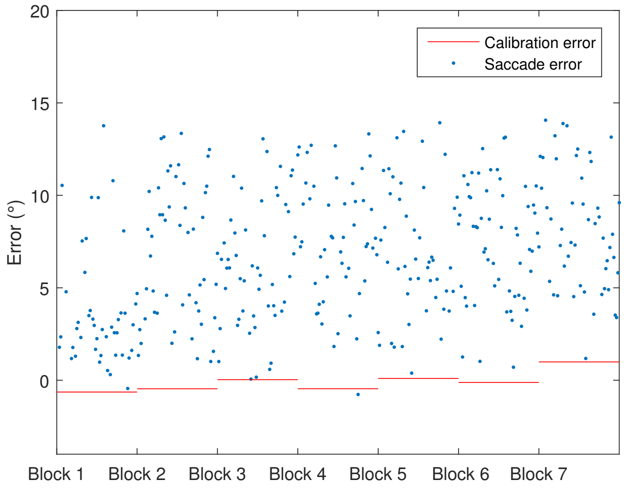

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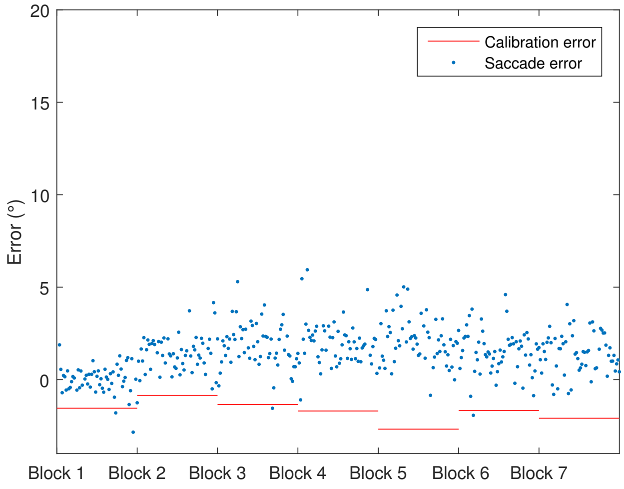

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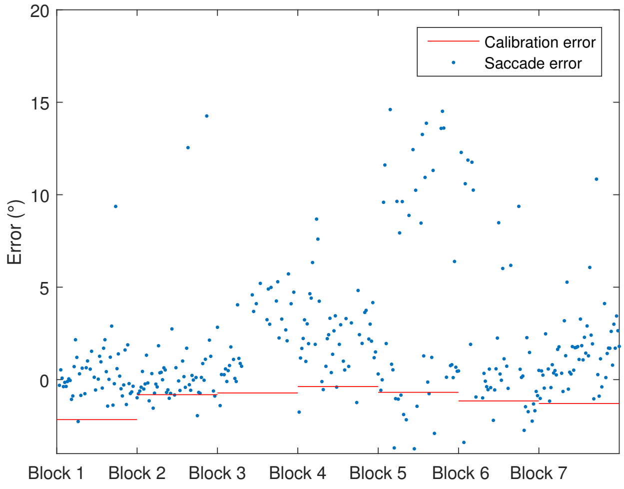

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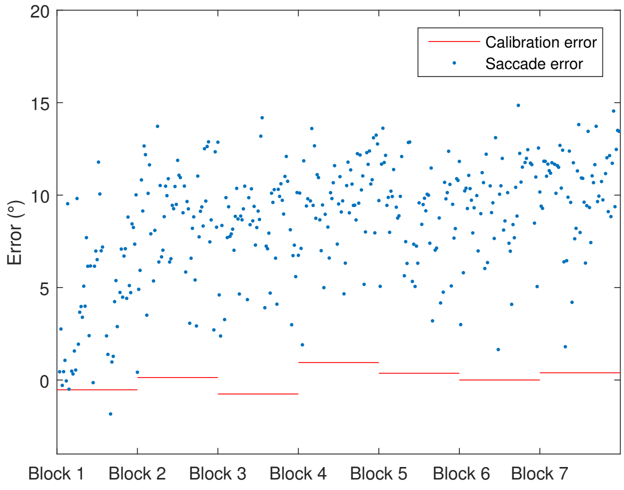

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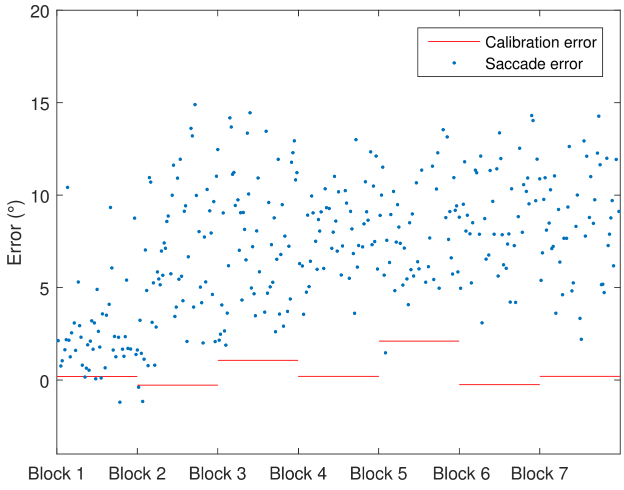

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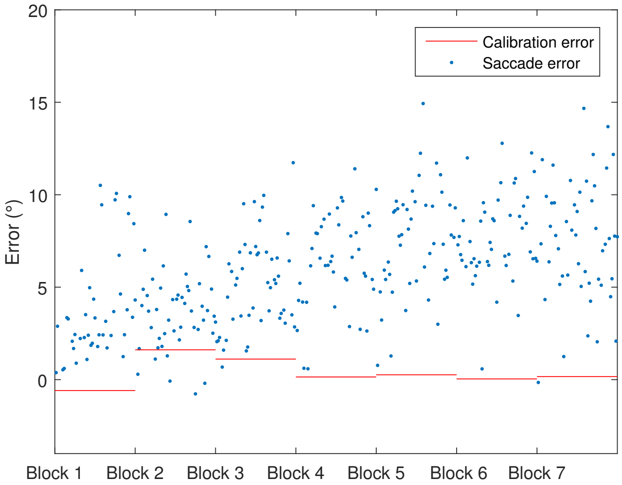

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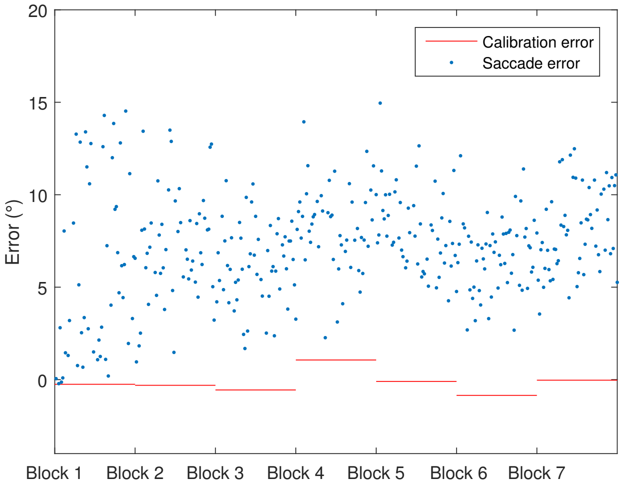

Amplitude errors for subject 12

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