École polytechnique de Louvain

Studying dynamic tracking by the hand and the eyes

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Abstract

Most of our daily movements are coordinated in a very natural way and seem easy to achieve. However, the mechanisms underlying our ability to perform such movements with precision are highly complex and require the integration of a great deal of information.

The objective of this work is to analyze the visual and manual tracking mechanisms of a target in dynamic condition (passive and active). By means of four experimental conditions assigned to sixteen participants with the KINARM robot, we reflect on the interest of a comparison between active and passive conditions. We also discuss the presence of a possible learning effect.

The results are used to advance research on the subject by confirming some of the data in the scientific literature and suggesting avenues for reflection on the study of the mechanisms underlying our movements.

Contents

1 Introduction

1.1 General introduction

In our everyday life, we use our hands to pick, throw or catch up objects. To achieve this task that may seems simple or natural, our brain is in fact doing an amazing and complex work [7]. It has to gather a huge number of different information together. The knowledge of the surrounding environment and the needed data could come from various sensors which could be visual (eye), proprioceptic (the fact that we know in which position our body and our members are) or haptic (skin)[1]. These data are then used to make the most accurate movement as possible. The goal of this work is to study some parts of this complex mechanism.
In order to analyze the visual and manual monitoring mechanisms of a target in dynamic condition (passive and active), we conducted a study with 16 subjects. Before discussing the method, the results obtained and before discussing them, we propose in the following section a state of the art of the theoretical concepts underlying our study.

1.2 State of the art

1.2.1 Eye movement

Thanks to 6 muscles, we are able to move our eyes to focus our attention on what we want [11]. This is an unbelievable useful function of the body. In contrast of what most people think, the way the eye works is far from a camera which takes a dozen of pictures per second.

If the information transferred from the eyes to the brain was taken and displayed, the quality of this information would be really low [21]. The only region of the vision where the quality of the image is accurate is called the sharp central vision (also called foveal region) [13]. The name foveal region comes from the fovea centralis which is the region in the eyes[2] where the number of cones[3] is the highest [14].

What makes the world the way we see it is a highly complex imagery treatment made by our brain taking in account the actual vision of both eyes but also guesses from the information from a few seconds earlier, our knowledge of the environment... [6] It's therefore very important that the foveal vision with the detailed and up to date data follows the objects or places we want to focus on. In order to achieve

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[1] It could be acoustic, but it's not the case studied here.

[2] More precisely on the retina.

[3] Cones or cone cells are the photo receptors which are able to pick up light and differentiate the wavelength.

this, the eyes can move in two different ways: by saccades or by smooth pursuit [13].

Saccades

A saccade is a quick movement of the eye from a point A to B. It's non-adaptative which means once the decision is taken it will not change even if new information is added during the latency or during the movement [14]. A saccade is characterized by [20] an amplitude (distance between A and B), a duration (time it takes to go from A to B), a latency (time between the decision of the saccade and the beginning of it), a gain (ratio between actual saccade and desired saccade) and a maximum velocity as shown in figure 1.

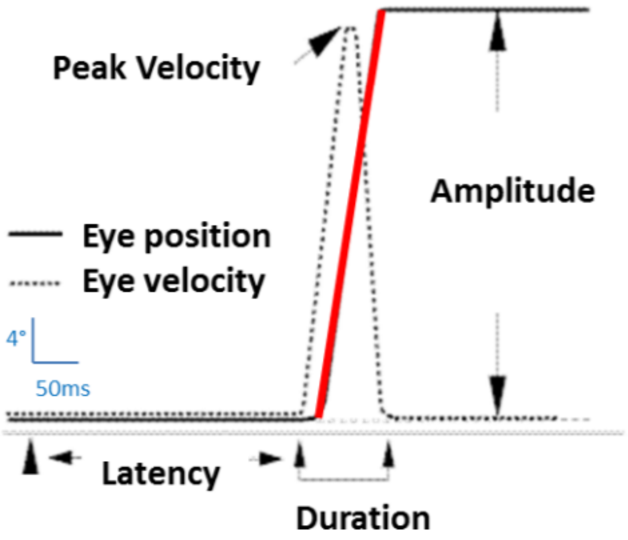

Figure 1: Saccade

Saccades are used at two different moments. The most obvious example is when we want to look at something we are actually not looking at which requires an eye movement [16], but there are also what are called "catch-up saccades". Catch-up saccades are useful when smooth pursuit (which is detailed just after) is to slow or to imprecise. The eye then make a jump to restore the correct position [13].

Despite the fact that saccades are useful, it alter the vision. During a saccade the movement of the eye is rapid and diminishes the quantity and the quality of data collected by the eyes.

Smooth pursuit

The second way in which the eyes can move is the smooth pursuit. This is preferable to saccades as it keeps tracking a moving object without altering the quality of the vision. The issue is that it cannot work properly above a certain velocity which is about $30°/s$ [14].

As shown in figure 2 the smooth pursuit is characterized by an initial acceleration, a peak velocity and a latency.

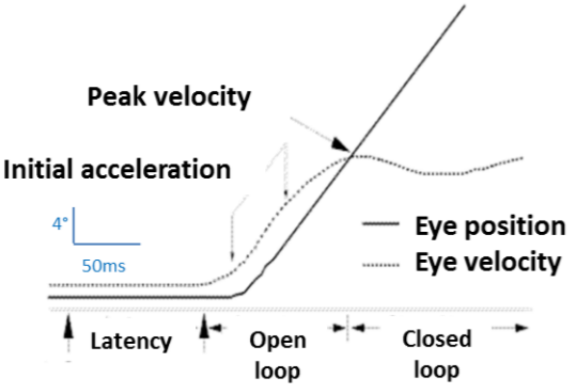

Figure 2: Smooth pursuit

Pursuit is less easy to characterized and is not as stereotyped as saccades. As well explained by the University of Liverpool (2019) [20], it's composed of two phases: ignition and maintenance. The ignition is composed of an initial acceleration of 100 ms based on some knowledge the brain has on the target. The first 20 ms are an acceleration which has always the same value whereas the 80 ms that follow are adapted to the target velocity and position. This is an open circuit such as shown in figure 3. The maintenance is a closed loop that aim to constantly adapt the velocity of the smooth pursuit to the target.

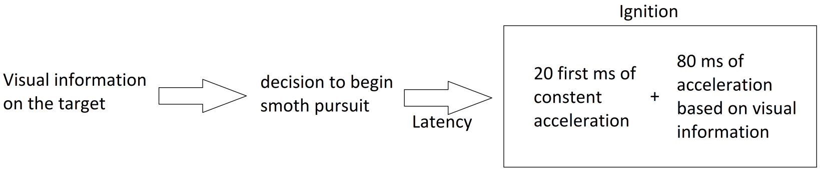

Figure 3: Ignition open loop during the smooth pursuit process

Graphical representation

Figure 4 below shows a typical trajectory with smooth pursuit (in blue) and saccades (in red).

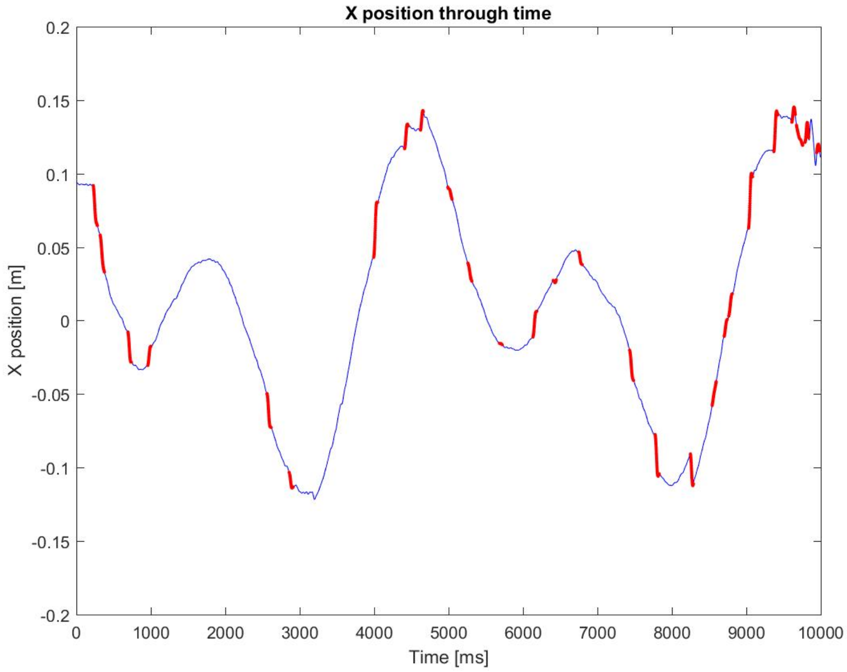

Figure 4: Graphical representation of smooth pursuit in blue and saccades in red. Subject 1 condition A

1.2.2 Hand movement

When a movement is executed, both vision and proprioception information are used to determine the position and orientation of the hand.

Several studies show the importance of the existence of both proprioceptive and visual information in the production of goal-oriented movement. Indeed, although subjects who are proprioceptively disaffected are able to perform movements, they are significantly less accurate than in healthy subjects when manual activities are performed without hand vision [17]. Studies also show that vision allows accurate movements to be achieved despite significant proprioceptive deficits [17].

This section focuses on information related to proprioception as such.

Proprioception is based on two types of information that human beings can use to find out where their limbs are: related and efferent information [5]. Efferent information provides a valuation of expected posture and could provide information in advance while the related pathways provide delayed feedback of posture. This feedback is obtained from skin, muscles and joints where all receptors can provide information on the position of the arm and hand relative to the body [5].

The manipulation of the object itself begins when the tactical kinesthetic surface of analysis (tactile fovea) comes into contact with the object. The movements are accompanied by a continuous change in the flow of proprioceptive joint and muscle reassignments that reflect changes in the position of the limb during the movement [15]. The trajectory of the movement is here indicative of the corrections likely to occur during the execution of the program [15]. Also, the kinematic characteristics of the trajectory and in particular its deceleration at the end of the stroke contribute to the emission of the proprioceptive phasic signal calibrating the final position [15]. Studies show that the position of the hand after rapid movement is better localized than after slow movement and that the presence of a mechanical stop at the end of the movement also contributes to making the final location of the limb more accurate [15].

As for the information resulting from tactile contact with the target, it is susceptible to spatial calibration. They can therefore help to readjust the member's projection program, they can also, when present, compensate for the absence of visual cues of terminal trajectory correction and contribute to its accuracy [15].

With regard to the issue of active and passive movements in proprioception, studies show that active body movements are superior to passive body movements in adaptive capacities [8]. An attempt to explain this would be that the position of the limb would be more accurate when the muscle or movement has been actively mobilized rather than passively [8]. This would be due to information from the different muscles (and more specifically, within muscle spindles) involved in voluntary movements that are absent during a passive movement [8].

1.2.3 Eye-Hand coordination

The eye-hand coordination is a coordinate control of the eyes and one or two hand(s). When such a situation appears, the body does not treat the two tasks independently. The signals that are headed for the hands (or eyes) can be shared with the eyes (or hands), this is called action for vision (or vision for action).

Research has shown the influence of the arm motor system on the oculomotor system during target tracking tasks [9]. Indeed, when an individual pursues with his eyes a target moved by the observer's arm (self-moved target tracking), the performance of this smooth visual tracking system (smooth pursuit) is better than when the observer follows with the eyes a target moved by an external individual (eye-alone tracking) [9]. This shows that an individual can pursue a visual target more precisely if that target is moved by the same individual's hand [9]. Such coordination control is the result of an exchange of sensory and motor information from the arm motor system to the smooth tracking system when they are both involved in a common task : the pursuit of a visual target [9]. This mechanism is explained in detail below, in the section 1.2.4 on internal models.

Indeed Steinbach and Held (1968) have been the ones to show that visual eye tracking is better in active movement than in passive movement[4]. This observation can suggest two things: the afferent[5] signal intended toward the arm is used to help the guidance of the eyes either the hands and the eyes have shared information. These authors suggest that if visual tracking in active condition is better than in passive condition, it is because the oculomotor system anticipates the future movement of the target by using muscle motor control signals [4].

1.2.4 Internal model

The motor control is the study of how organisms make accurate goal-directed movements [18]. To achieve such a goal, individuals must build internal models of the body and the world. The term model means that the brain models the interaction of sensory and motor systems between them, as well as their interaction with the physical world [10]. The internal term means that this model is internalized by the brain and implemented within specific neural circuits [10]. Basically, the internal models represent the input-output properties of the computational motor control [11].

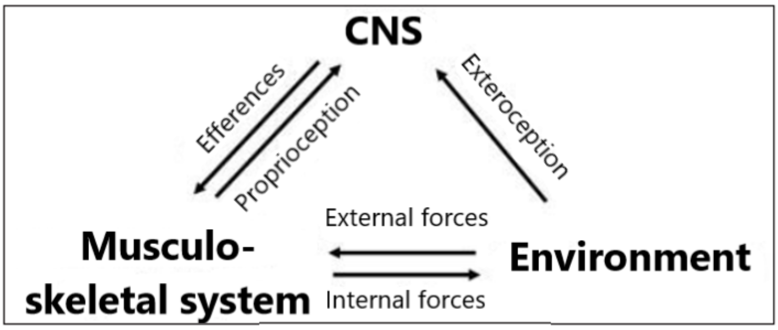

Figure 5: Motor behavior results from the interaction between the environment, the musculo-skeletal system and the CNS[6][17]

The internal models have the purpose of solving a whole series of limitations faced by the sensorimotor loop in fast actions [11] [18]. First, the sensory feedback loop can be noisy and delayed, which can make movements imprecise and unstable [11] [18]. A second problem that the sensorimotor loop has to face is that the

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[4] Has explained in section 2.3: "Active" means that the subject has to actively move his hand whereas "passive" means that the hand is externally moved.

[5] An afferent signal is from the brain to an other part of the body whereas an efferent signal is from the body to the brain.

[6] Central Nervous System.

relationship between a motor command and the movement it produces is variable, as the body and environment can both change and as there can be a delay in neuronal transmission, processing and integration [11] [18]. An illustration of the fact that delays in the sensorimotor loop are a problem for real-time feedback control would be the case of a person taking a shower in a bathroom they have never used before [18]. In this case, the naive user will turn on the shower and want to increase the water temperature. As the time between the temperature adjustment on the button and the feeling of heat is long, the adjustments on the button will not have an immediate effect on the water temperature and the individual will certainly continue to turn the button towards a higher heat. By the time the actual temperature is felt, it will certainly be too high. The individual will therefore probably try to cool quickly the water temperature, by turning the knob towards a lower temperature. However, the temperature continues to increase, which is why the individual continues to try to cool the water temperature and when the temperature is felt by the individual, it is now too cold. All this can be avoided if the individual has a good knowledge of the functioning of the shower button in question, which then allows him to predict the sensory consequences of his motor actions, which is what one type of internal model does.

Indeed, multiple researches show that there are two types of internal model: the forward model and the inverse model.

Through predictions, the forward model transforms motor commands into sensory consequences and produces both a lifetime of calibrated movements and an estimation of the state of the body and the world around it [18]. It is used to predict the sensory outcome of the generated motor commands [11]. Note that the input of this model is the copy of motor command, also called "efference copy" [11]. The efferent motor signals support the corollary discharge and are therefore used to predict the consequences of actions before sensory feedback is available [11] [18]. Because the efferent copy is motor coordinated and the corollary discharge is sensory coordinated, forward model provides a faster and less noisy control loop that facilitates rapid movements [11].

Forward models establish a causal link between the action and its sensory and dynamic consequences from the state of the system and the motor control [10]. An illustrative example of this model is the possibility of accurately predicting the trajectory of a ball you want to catch; the sensorimotor system that the CNS must control to catch this ball is represented by the content of the internal model [10].

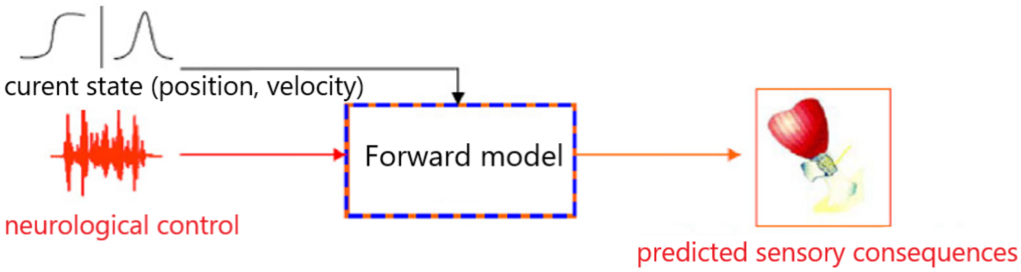

Figure 6: Forward model [10]

The second type of internal model is the inverse model. The role of this model is to provide an adapted neural control based on the current state of the system and the desired motion [10]. It is also called feedback controller [11]. The inverse internal model establishes a non-causal (inverse) relationship between sensory and dynamic signals and the motor control. Thus, it represents the inverse transformation between action and its consequences on the body and the environment.

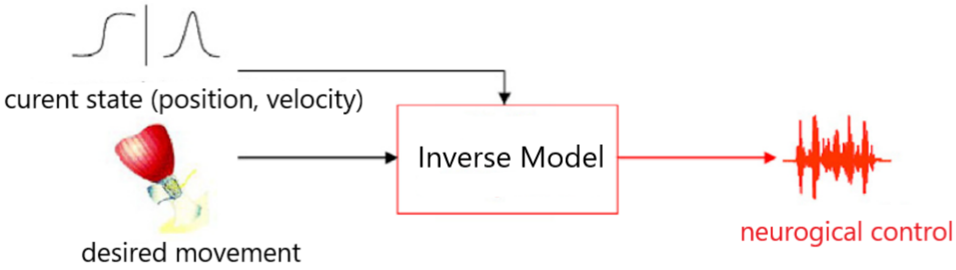

Figure 7: Invers model [10]

Inverse and forward models perform different but complementary operations. Indeed, the inverse model allows to calculate the motor controls on the basis of information such as the state of the system and the desired movement; in parallel, the forward model allows to process the information related to the sensory states by using the efference copy of the motor control [10]. These two models provide, first, a rapid prediction of the outcome of a motor command and, secondly, a delayed copy of that prediction, which will match in time with the actual feedback arising from the movement [12].

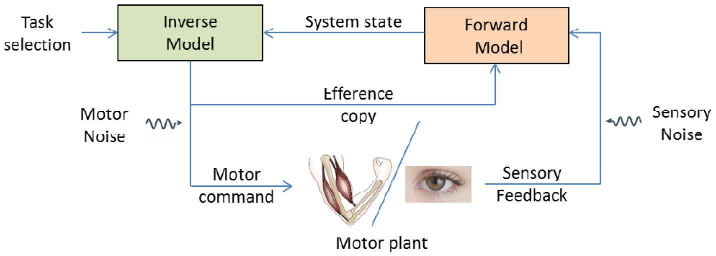

Figure 8: Role of forward and inverse models in motor behavior [11]

1.3 Aim of the work

This work studies the oculomotor synchronization in dynamic motion. Through a protocol that we implemented and using the KINARM robot, we collected and analyzed data from volunteer participants in order to extract the information necessary for a better understanding of this type of coordination.

This understanding is important in several ways. Beyond the fact that answering fundamental scientific question and understanding the world in which we are is a goal itself, the understanding has concrete applications. First of all understand how the human body works is crucial in order to be able to repair it (build appropriate prothesis, establish brain operations, give adequate motor exercises to rehabilitate people after accident...). Secondly it will offer the possibility to improve human (with exosqueleton, robot controlled by thought, extremely precise camera linked to the brain...). Finally understand how the mechanism works will make possible the prediction of how human will behave in new situations never faced before (in space, after a brain operation ...)

The axes in order to understand the complex behavior are multiple.

First, we wish to measure the importance of vision (conditions with or without vision) in active or passive movement. We also hope to achieve a better understanding of the complex mechanism that coordinates the movement of the arms and eyes and study how they interact with each other. To do this we will also have to distinguish between the saccades and smooth pursuit mechanisms, this point will be detailed in section 4.4

An other goal is to examine the presence of a possible learning process through time. This would be transduced by an amelioration between the beginning and the end of the experiment for each subject.

Finally, the goal will be to see if internal models (forward and inverse) are still consistent in dynamic situation and improve, confirm or eventually re-think those models.

2 Methods

As said in 1.1, the brain uses a complex mechanism which need a lot of different sources of data to compute a decent result. One efficient way to study complex mechanisms is by trying to separate the different sub-mechanisms to see and understand how they work. In this section we present the four conditions that we implemented in our study to explore the visuo-proprioceptic mechanism.

2.1 Material

2.1.1 KINARM robot

Thanks to the KINARM robot, shown in figure 9, it has been possible to create particular situations which do not occur in everyday life and record data in order to understand how human beings manage the various visuo-proprioceptic tasks.

Figure 9: KINARM [1]

The robot KINARM is composed of 2 handles which can move in an a plane parallel to the ground that we will call the XY-plane. On the top of the robot a screen is oriented downwards in order that the image displayed by this screen is reflected by a mirror toward the eyes of the subject. The subject is seated on a chair next to the robot and has access to the handles with his hands.

The goal of this installation is to create a virtual reality in front of the subject, a reality where the subject can interact in precise and particular conditions i.e. following a moving target with the hand but without seeing the position of the hand. This reality is created by the screen but thanks to the equal distance screen-mirror and mirror-hand, the subject imagines it at the level of his hand. This is shown in figure 10.

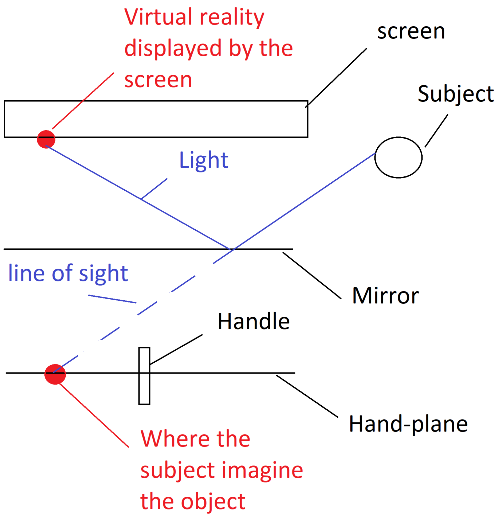

Figure 10: Virtual reality

In the following experiments this reality can show two important things :

- A target : a colored dot of several centimeters of radius, which can move or not.
- The feedback of the hand : another dot, which is white, a bit smaller than the target which indicates the position of the hands in real time. In function of the experiment this feedback will be activated or not.

2.1.2 Gaze tracker

The gaze-tracking is one of the main components of our work to analyze the oculo-motor system and the coordination between the hand and the eye. The KINARM robot uses the Eye Link 1000 Plus implemented by the SR-Research EyeLink®.[7]

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[7] For more precision about the device follow [19].

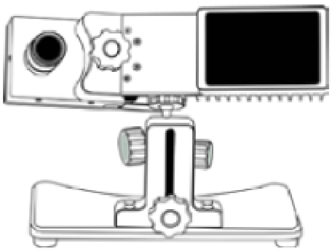
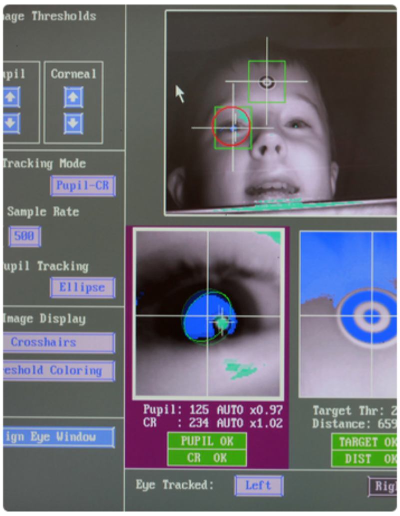


Figure 11: EyeLink 1000 Plus [19]

Before taking any measure, this device requires a quick calibration followed by a confirmation [2]. For the calibration the subject must look at 13 different targets appearing on the screen and the subject repeats this task a second time to validate the calibration.

A small target is stick on the head of the subject to provide the position of the eye relative to the head. This is important for tracking when the EyeLink loses the signal.



Tracking Mode: Pupil-CR
Sample Rate: 500
upil Tracking: Ellipse

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Pupil: 125 AUTO x0.97
CR   : 234 AUTO x1.02
Target Thr: 2
Distance: 659
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Eye Tracked: Left

Figure 12: Exemple EyeLink software [2]

2.2 Subjects

Twenty-one subjects passed the experiment but, due to some noise, five of them had data that could not be processed. In particular, the eye signal was of poor quality due to signal losses at the gaze tracker. Consequently, data from sixteen of them were kept for the following analyses. It's important to understand that the subjects were removed before any analysis and way before understanding what was happening and plotting the results. The rejection criterion was only the quality of the eye signal.

In these sixteen subjects aged between 18 and 49 years old, nine of them are men. Every subject is right-handed.

Two of the subjects were not naive about the experiment. This fact will be taken into account in the analysis of our results in order to determine the presence of a possible learning effect.

The order of the conditions and the order of the trials were different for each subject in order to avoid the influence between separated conditions. Indeed, by doing so, we've tried to control a possible sequencing effect.

None of the participants presented any motor disabilities. All of them gave their consent to participate at this experiment and agreed that their results could be submitted to further analysis. All also agreed that the results could be published anonymously.

2.3 Experiment

Four conditions have been done during this study. Two of them are called "active", which means that the subject has to move actively his hand whereas the two other ones are called "passive" with the movement of the arm directed by the motors of the KINARM. In the two different cases (passive or active) the subject can benefit from visual feedback (FB) of his hand or not. This feedback is represented by a white dot on the screen which shows the exact location of the subject's hand.
The four conditions have been designed with the combination of the two variants just mentioned (active - passive and FB - no FB).

	Active	Passive
FB	Condition A	Condition C
No FB	Condition B	Condition D

Table 1: Different conditions

During the four conditions, the subject is seated on a chair as in figure 9, he activates the right handle with his right hand. The position of the handle and his gaze are recorded.

For each condition, the subject makes 30 trials which implies that the experiment is composed of 120 trials.

Before each condition a reference measure is performed. For this measure, the subject must aim several static targets with the gaze and with the hand without visual feedback from the hand.

2.3.1 Condition A

As explain previously and shown in table 1, the first block of trial concerns an active movement with feedback.

Before any recorded data, there is a time we will call "preparation task". A red target appears on the screen and the subject has to reach the target with his hand (through the handle of course). The subject has a feedback of his hand which allows him to go exactly on the target. Then when he is in position (thus target and hand in the same position) the target turns green, which means that the data collection and interesting part of the condition will begin.

The target then starts moving in an unpredictable smooth path [8]. The goal of the subject is to follow the target with his hand.

The term "follow" here is not the same as "following a car on the road" but rather "being on the top of the target", or "exactly at the same place at every moment". This was explicitly mentioned to every participant. As one of the important components of the study is the distance between the hand and the target, it's crucial that we avoid a constant delay between hand and target. Of course it's impossible to be perfectly on top of the target at every moment but what is avoidable is a large constant time-delay.

2.3.2 Condition B

The condition B is also about an active movement but the difference here is that the subject doesn't see his hand and thus and has no idea of where it is. He has to guess the position with his proprio-sensors (and not his vision as in A or any life-experiences).

Note that the preparation task is the same than in A, the subject still has the feedback of his hand until the data collection begins so he can go to the exact same place than the target. The hand feedback disappears when the target turns green and just before it goes in unpredictable smooth path.

2.3.3 Condition C

As said in table 1, the conditions C and D are passive conditions which means that the robot will guide the hand of the subject.

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[8] Those paths are explained in details in section 2.4.

As in condition A and B, the preparation task is the same. Then when the hand of the subject and the target are on the same place, the target turns green and the robot begins to move in unpredictable smooth trajectories.

As the robot executes the exact same path with the handle than the green target, the feedback of the hand and the target are at the exact same coordinate for any time[9]. The target position (which is the same than the hand position) is indicated to the subject.

The task of the subject is to follow his hand with his gaze.

2.3.4 Condition D

The same than condition C but with one difference: there is no feedback of the hand. After the preparation task the feedback disappears just before the robot begins to move. The subject is then in front of a totally black screen.

The goal of the subject is to follow his unseen hand with his gaze thus to "guess" where his hand is.

2.4 Path of the target

As the goal of the four conditions mentioned just above is to study the reaction of subjects in dynamic motion, the path used is important.

The shape must be unpredictable, does not have to be too simple nor too complicated, high velocity gradient are not recommended and the path must fit in the screen shape[10]. The shapes we used, shown in figure 13, are the same than in the article [3].

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[9] In condition A and B there was a distance Hand-Target due to error of the subject.

[10] To use the space on the screen it's better not to be too far from a squared shape.

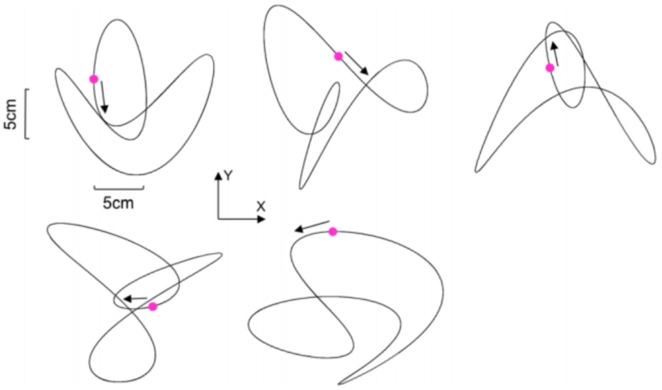


Figure 13: Five trajectories [3]

These 2D shapes are made of two sinusoidal curves that dictated the x and y coordinates. The equations are the following :

$$x_t = A_{1x} cos(\omega t) + A_{2x} cos(h_x \omega t - \phi_x) \tag{1}$$

$$y_t = A_{1y} cos(\omega t) + A_{2y} cos(h_y \omega t - \phi_y) \tag{2}$$

The multiple values of the parameters that gave the five shapes shown in figure 13 are detailed in table 2.

Trajectory	A_{1x} (cm)	A_{2x} (cm)	$Harmonic_x$	$Phase_x$ (°)	A_{1y}	A_{2y}	$Harmonic_y$	$Phase_y$ (°)
1	5	5	2	45	5	5	3	-135
2	4	5	2	-60	3	5	3	-135
3	4	5.1	3	-60	4	5.2	2	-135
4	5	5	3	90	3.4	5	2	45
5	5.1	5.2	2	-90	4	5	3	22.5

Table 2: Trajectories parameters [3]

The parameter ω is fixed at $\frac{2\pi}{5}$ so that every trajectory lasts 5 seconds. During the experiment one trial takes 10 seconds and is composed of 2 times the same path. The 10 seconds trajectories stay unpredictable. The subject even doesn't realize that the trajectory is repeated two times.

3 Programming Environment

In order to achieve the experiment just described, the robot KINARM has been used. As already mentioned in section 2.1, this robot is composed of 2 handles, 1 screen and one eye tracker. The whole system is linked to a computer as shown in figure 14. This computer controls the robot.

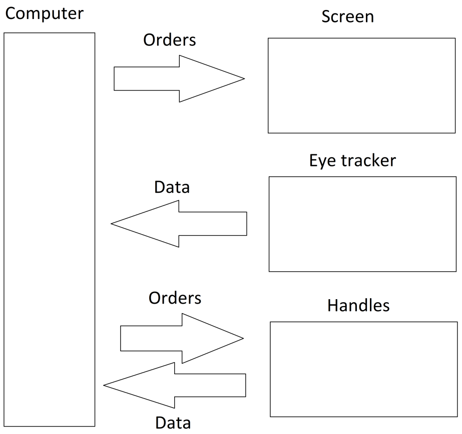


Figure 14: Link between the computer and the KINARM

The computer takes the data from 2 sensors (the eye tracker and the handles) and sends back orders to two elements of the KINARM (the screen and the handles). Thus the handles have several sensors which collect information and transmit it to the computer but can also move through the activation of the motors.

3.1 Software and data organization

The software provided with the KINARM robot to control it, called Dexterit-E, is using the data from the sensors and two different files in order to run the robot : a .dlm file and a .dtp.

The .dlm is generated by a simulink program described in the section 3.2. It contains the information on the different trajectories (shapes, starting points, velocities) and the parameters that have to be recorded. These files also contain the reverse kinematic so that the robot can provide the adequate forces and torques in order to achieve the passive movement for the given paths. Once written the simulink program is launched and the .dlm does not change from one participant to another.

The .dtp is more flexible and some parts vary from one participant to another. This file is generated by Dexter-E itself in an interface that is provided for that purpose. It allows the user to choose the adequate trajectory, the value of some parameters such as the various time delays and the features of the target (shape and color). For each participant, it's also the moment to indicate the order of the trials and if the hand feedback is displayed or not.

Thanks to those files and the sensors, Dexterit-E runs the experiment and collects the data which are saved in a .zip file. Then the data can be analyzed either with matlab or directly displayed graphically on the computer thanks to a software called Dexterit-E Explorer.

3.2 Simulink model

Simulink is a graphical programming environment for modeling, simulating and analyzing multidomain dynamical systems. It's developed by Mathwork and is one of the numerous tools of the MATLAB environment. The interface is a graphical block diagramming tool.

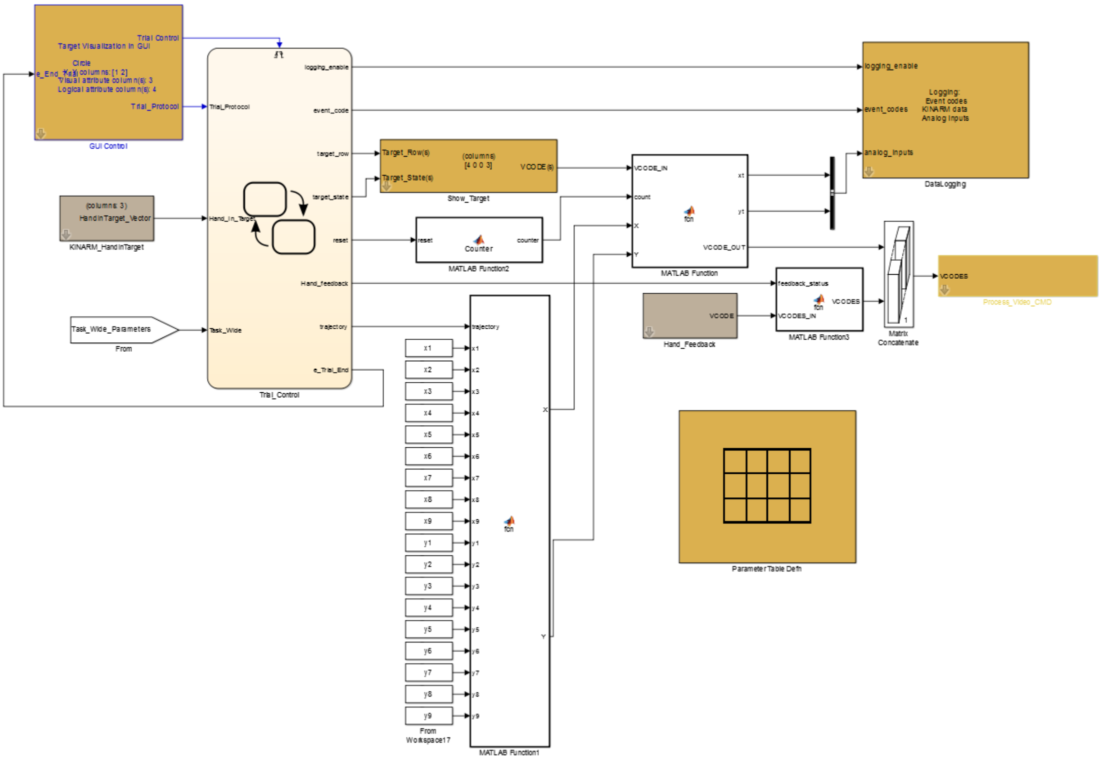


Figure 15: Simulink model of the active experiments

Figure 15 shows the blocks organization of the active experiments (A and B). The main blocks are the following:

- The counter: which is responsible to count the time
- Data logging: which decides which parameters should be recorded
- Gui control which takes in charge the communication between the task program (.dlm file) and the Dexterit-E GUI (which runs on a separate windows-based computer)
- Task wilde parameters (input) : that comes from the .dtp file
- The trajectories (input): from x1 to x9 and from y1 to y9 are all imported from the workspace of matlab after an independent program has ran.[11]
- Hand feedback (input) : gives the position of the handles
- Vcodes (output) : is the goal of the program. Thanks to this Vcodes the screen will be able to display the images wanted
- State flow chart (central piece which link everything) is detailed in section 3.3

3.3 Stateflow chart

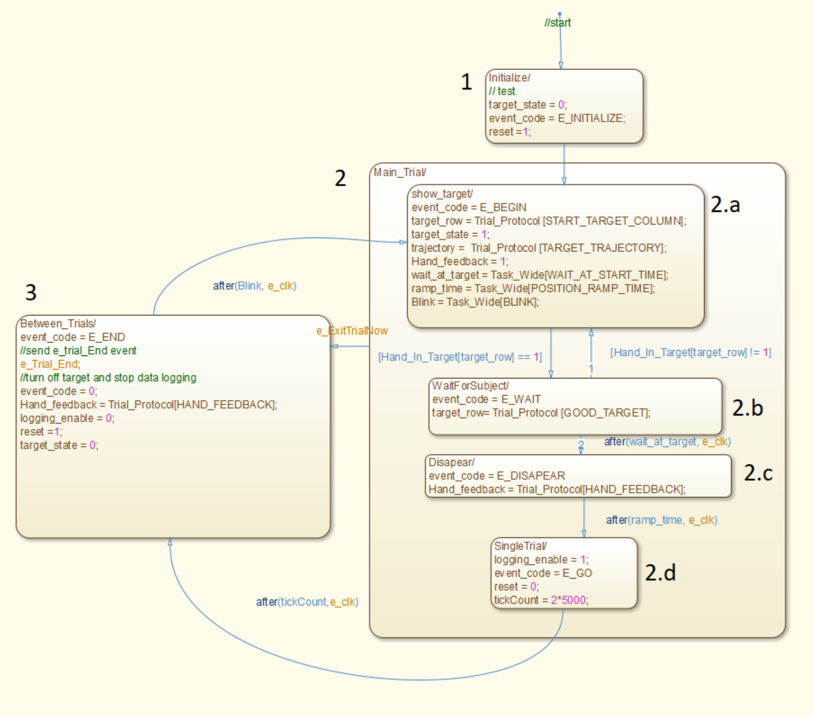
The stateflow chart is a graphical way of programming where states are defined and linked together by conditions.

3.3.1 Active

Figure 16 shows our program for experiences A and B.

---

[11] Only 5 trajectories within the 9 programmed have been used.



```
Initialize/
// test
target_state = 0;
event_code = E_INITIALIZE;
reset =1;
```

```
Main_Trial/
```

```
show_target/
event_code = E_BEGIN
target_row = Trial_Protocol [START_TARGET_COLUMN];
target_state = 1;
trajectory =  Trial_Protocol [TARGET_TRAJECTORY];
Hand_feedback = 1;
wait_at_target = Task_Wide[WAIT_AT_START_TIME];
ramp_time = Task_Wide[POSITION_RAMP_TIME];
Blink = Task_Wide[BLINK];
```

```
WaitForSubject/
event_code = E_WAIT
target_row= Trial_Protocol [GOOD_TARGET];
```

```
Disapear/
event_code = E_DISAPEAR
Hand_feedback = Trial_Protocol[HAND_FEEDBACK];
```

```
SingleTrial/
logging_enable = 1;
event_code = E_GO
reset = 0;
tickCount = 2*5000;
```

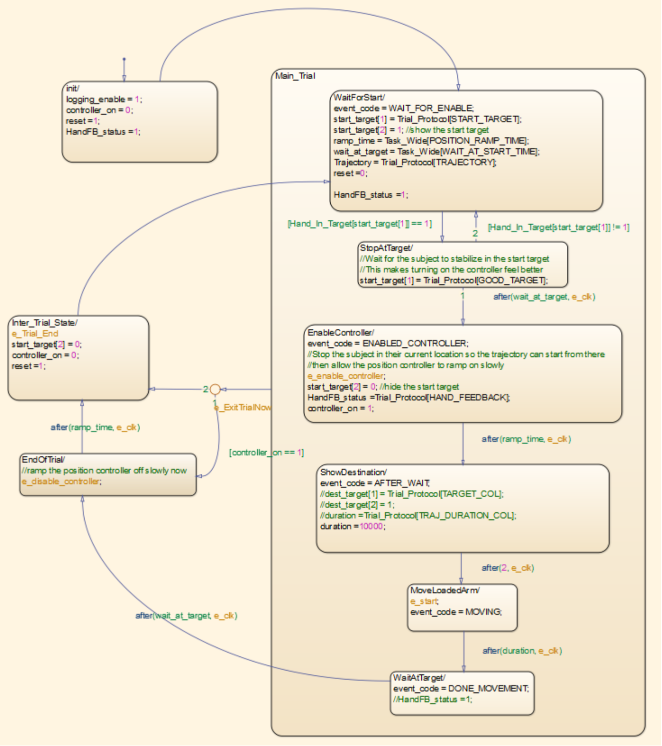
```
Between_Trials/
event_code = E_END
//send e_trial_End event
e_Trial_End;
//turn off target and stop data logging
event_code = 0;
Hand_feedback = Trial_Protocol[HAND_FEEDBACK];
logging_enable = 0;
reset =1;
target_state = 0;
```

Figure 16: The stateflow chart for exp A and B

- State 1 : Initialization. Set the variables in their initial state.
- State 2 : The main trial is the set of states and instructions that is read during on trial of 10 seconds.
  - State 2.a : shows the initial position of the trajectories on the screen and waits that the subject goes there with the handle.
  - State 2.b : is an intermediate state between the 2.a and 2.c, that ensures that the subject stays one second on the initial position.
  - State 2.c : makes the feedback disappear if needed (thus for exp B) before the target starts moving
  - State 2.d : the target moves during 10 seconds
- State 3 : set all the variables back to the initial state in order to be ready for the next trajectory.

3.3.2 Passive

Figure 17 shows our program for experiences C and D.



```
init/
logging_enable = 1;
controller_on = 0;
reset =1;
HandFB_status =1;
```

```
Main_Trial
```

```
WaitForStart/
event_code = WAIT_FOR_ENABLE;
start_target[1] = Trial_Protocol[START_TARGET];
start_target[2] = 1; //show the start target
ramp_time = Task_Wide[POSITION_RAMP_TIME];
wait_at_target = Task_Wide[WAIT_AT_START_TIME];
Trajectory = Trial_Protocol[TRAJECTORY];
reset =0;

HandFB_status =1;
```

```
StopAtTarget/
//Wait for the subject to stabilize in the start target
//This makes turning on the controller feel better
start_target[1] = Trial_Protocol[GOOD_TARGET];
```

```
Inter_Trial_State/
e_Trial_End
start_target[2] = 0;
controller_on = 0;
reset =1;
```

```
EnableController/
event_code = ENABLED_CONTROLLER;
//Stop the subject in their current location so the trajectory can start from there
//then allow the position controller to ramp on slowly
e_enable_controller;
start_target[2] = 0; //hide the start target
HandFB_status =Trial_Protocol[HAND_FEEDBACK];
controller_on = 1;
```

```
EndOfTrial/
//ramp the position controller off slowly now
e_disable_controller;
```

```
ShowDestination/
event_code = AFTER_WAIT;
//dest_target[1] = Trial_Protocol[TARGET_COL];
//dest_target[2] = 1;
//duration =Trial_Protocol[TRAJ_DURATION_COL];
duration =10000;
```

```
MoveLoadedArm/
e_start;
event_code = MOVING;
```

```
WaitAtTarget/
event_code = DONE_MOVEMENT;
//HandFB_status =1;
```

Figure 17: The stateflow chart for exp C and D

4 Data processing

The data has been studied with matlab. The first step was to extract the correct data from the .zip file which are : the target position, the hand position and the eye position. After this step, the target and hand position were ready to be analyzed but the eye position needed to be treated. Indeed this signal was noisy, imprecise, incomplete and sometimes inconsistent. Most of these problems could be solved by the process explained below.

4.1 Blinks

The first step was to remove the blinks. During blinking, the gaze tracker loses the signal because it is no longer able to capture the pupil. This loss is represented numerically by an outlier (100,100) [m] when the target on the screen always stays in the plane ([-0.2;0.2], [0.1;0.4]) [m].

This happens when the signal is lost, the eye tracker then replaces the signal with this absurd value. Two reasons can explain this loss. First, the signal is physical not visible. This can be caused by closed eyes (for e.i. blinks) or the hair that fall and come in front of the eye. Figure 18 shows a blink. The second possibility, shown in fig 19 is that even if the eye is visible, the eye tracker is not able to identify correctly where the pupil is and thus is unable to calculate the position of the gaze. The second cause is the most consequent and the most frequent.

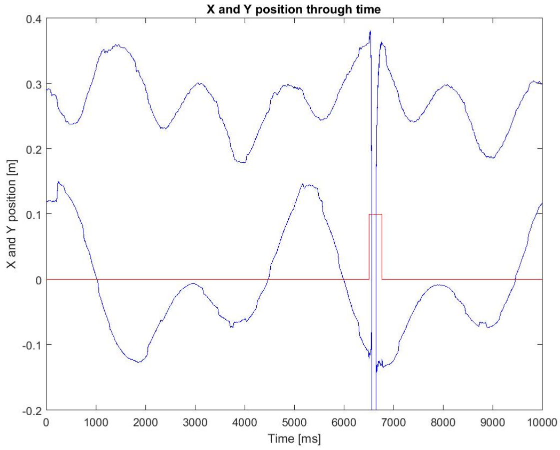


Figure 18: Blink in the X-eye signal. Subject 2, trial 63.

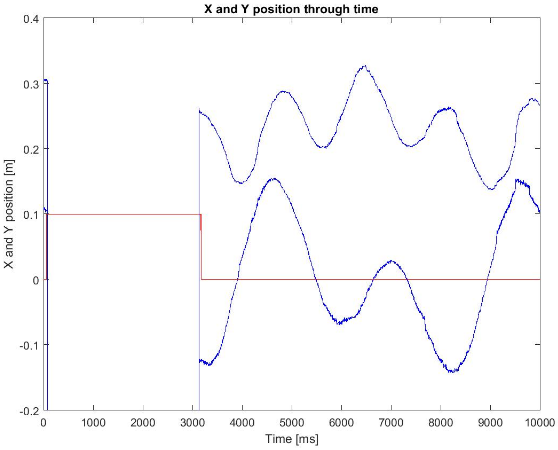


Figure 19: Data lost. Sujbect 5, trial 64.

Once the signal is lost, it's impossible to recover it. Two approaches are then possible. The first is to interpolate the missing signal and the second is to work with incomplete signal. The second method has been chosen for several reasons. Interpolate a signal means to guess some data and, if those data are used, it means that we study data which are not 100% reliable. Interpolate can be useful when the data absolutely need to be studied as a whole, here it's not the case, we just need data with a long period enough so that the behavior of the subject can be studied with the few last instants. When a lot of data are lost, the signal is not readable, to difficult to treat and induce incoherent results. We thus decided, on a treshold of 90% of good data for each subject, and thus work only with the results of 16 subjects on 21.

In order to remove the blinks the code blinkremover2.mat has been used which removes automatically the blinks, then the code MarkKinEyeBlink.mat is launched in order to verify manually and correct the first code (the first code detects the major cases but is unable to identify all specifics occurences).

4.2 Eye signals correction

In addition to the loss of signal, the eye tracker has a second default : it can induce constant error. To understand what happens, a brief explanation of how the tracker work is needed.

The tracker has two pieces of information : the position of a marker on your face[12] and the position of your pupil. The robot is then calibrated as explained in section 2. If the subject doesn't move his head but only his eye, the eye tracker is then able to calculate the angle of displacement and thus the spot where the subject

---

[12] Little sticker that is on the subject's cheek.

is looking on the screen. One problem is that some little constant errors arise due to imprecisions : the subject moves his head through the experiment, the measure of the first calibration is not perfect ...

To minimize those constant errors, extra data has been recorded before each experiment. These data will be used for a correction post-experiment. The goal of this post-experiment treatment is to fit the map of the 9 positions of the eyes on the 9 positions of the target. This is done by calculate a gain and an offset in X and Y and transform the eye signal into a new eye signal by the formula :

$$\begin{aligned} EyeSignal_{X,new} &= EyeSignal_X \cdot Gain_X + OffSet_X \\ EyeSignal_{Y,new} &= EyeSignal_Y \cdot Gain_Y + OffSet_Y \end{aligned} \tag{3}$$

As there are 9 points to adjust and 4 degrees of freedom, this calibration do not delete the error but minimize it.

4.3 Lowpass filter

The position of the eye is measured every millisecond. As the eye tracker has some noise[13], the position is unstable, as shown in figure 20.

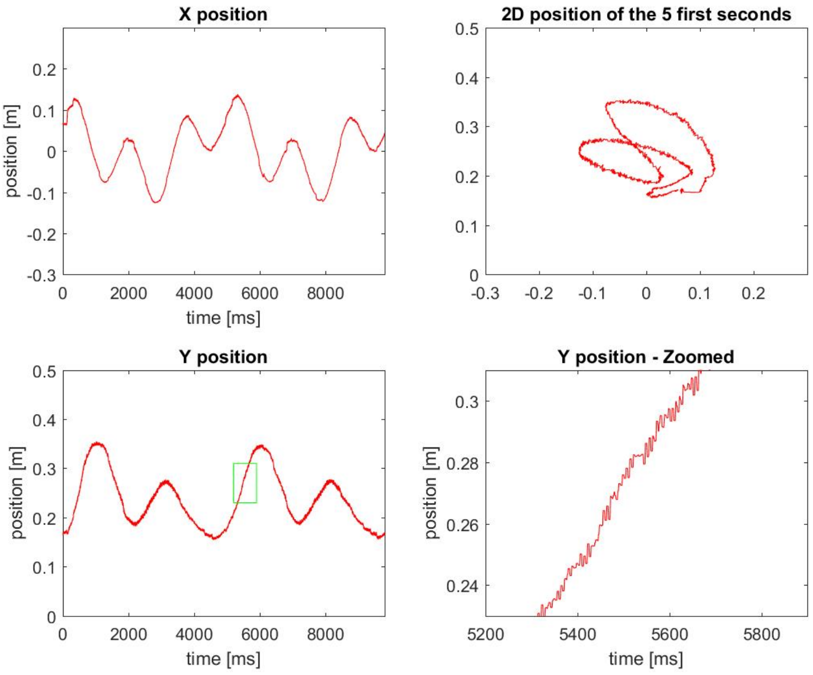


Figure 20: Filter off. Subject 2 trial 54.

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[13] Random imprecision on each measure.

In order to have a smooth signal and to be able to calculate the velocity, a low pass filter with a cutoff frequency of 25Hz is used. This filter allows a better analysis of the speed because it harmonizes the trajectory. The smooth data is displayed on figure 21

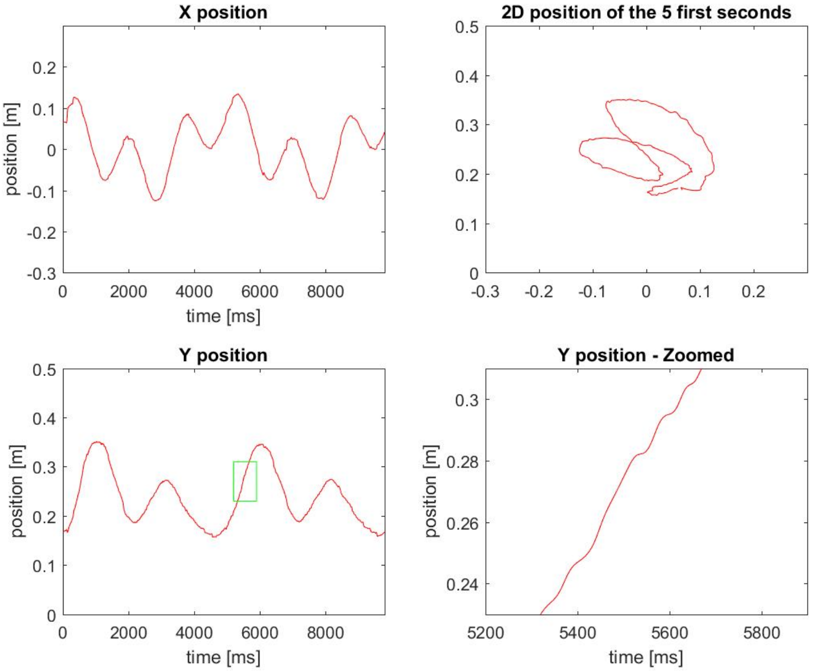

Figure 21: Filter on. Subject 2 trial 54.

4.4 Saccades and smooth pursuit

Once the noise is cleaned, the calibration taken in account and the inconsistent data are ruled out, the position and its derivatives can be analyzed. The last step of the data processing is to differentiate if the eye movement is in a saccade or in smooth pursuit for each step of time. Indeed this information is important to go further in the analyzes of the results as the mechanisms are different and need to be separated in order to be studied.

This has been done with the code saccadextractorXY2.m, and verified manually if the results were consistent. A saccade is defined by a velocity greater than 20 cm/s and an acceleration greater than 1200 cm/s^2.

5 Results

As the results of the experiment and the studied data are different between the active and passive condition it will be analyzed in two different sections (section 5.1 for the active and section 5.2 for the passive).

The way the results are presented is the same than the way they have been studied. First a typical trial is shown to have an intuition about what is happening, then a first evaluation is done where we calculate some representative numbers. If this seems to be an interesting track, a further analysis is made graphically in order to really understand what is happening and finally look if the detailed tables show a statistically significant result.

5.1 Active experiments

The instructions given to the subject for the active experiment only concern the hand. Subjects were asked to put their hands on the target as much as possible (and not to follow it). They were free to look where they want to in order to achieve the task.

5.1.1 Typical result

Before going into a more precise and mathematical point of view, figure 22 shows a typical result of condition A.

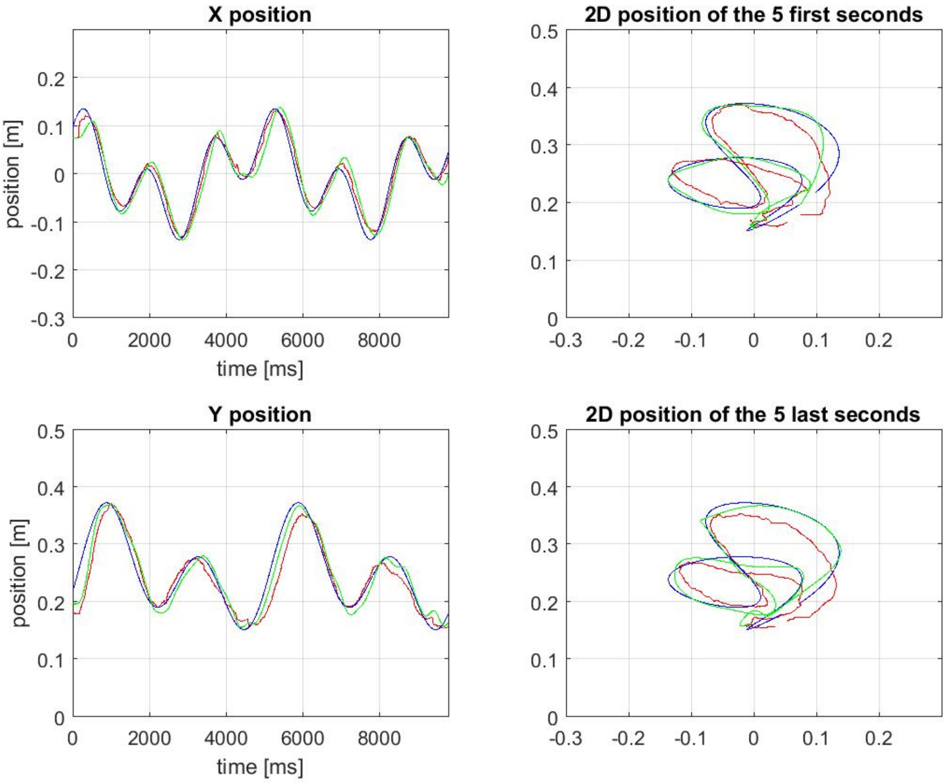

Figure 22: A typical trial of condition A. Here is subject 2 trial 22.

In blue we can see the target position, which is, as expected, a perfect sinusoidal curve. As explained earlier (section 2.4) the first 5 seconds and the last 5 seconds are exactly the same.

The hand position is represented in green. This curve is also relatively smooth. It is really close to the target position but with a certain imprecision. It seems that the imprecision is partially due to spatial imprecision but also due to a time delay. Indeed the green curve looks like the blue curve but slightly deformed and a little bit shifted to the right.

The position of the eyes is represented by the red curve. Even if it's clear that the red curve is similar to the others, it's definitely less smooth.

We can also see on the two graphs on the right that the three curves do not meet at the end of the stroke to close the loop. This is because some of the first and last data has not been drawn because they were less relevant and more chaotic.

The typical condition B is represented in figure 23 below.

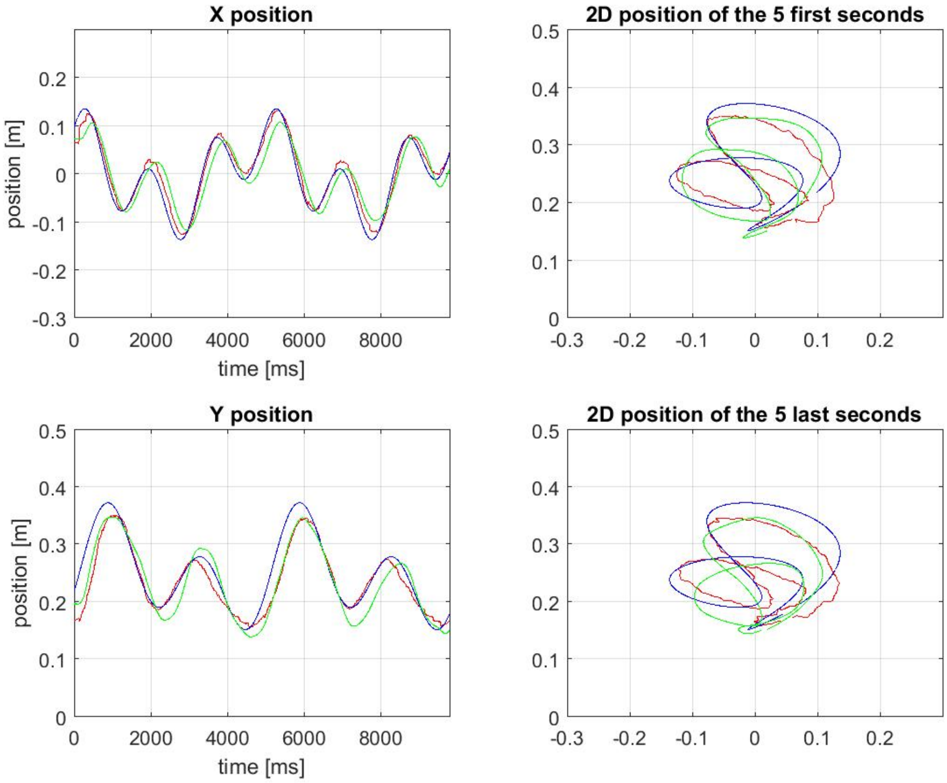

Figure 23: A typical trial of condition B. Here is subject 2 trial 54.

The trajectories of the curves in condition B are similar to those in condition A except that the imprecisions seem slightly more important.

5.1.2 Hand-Target error in absolute frame

The first analysis we did was to compare the variability in the Hand-Target distance at condition A with the distance at condition B. This average distance is shown in figure 24 .

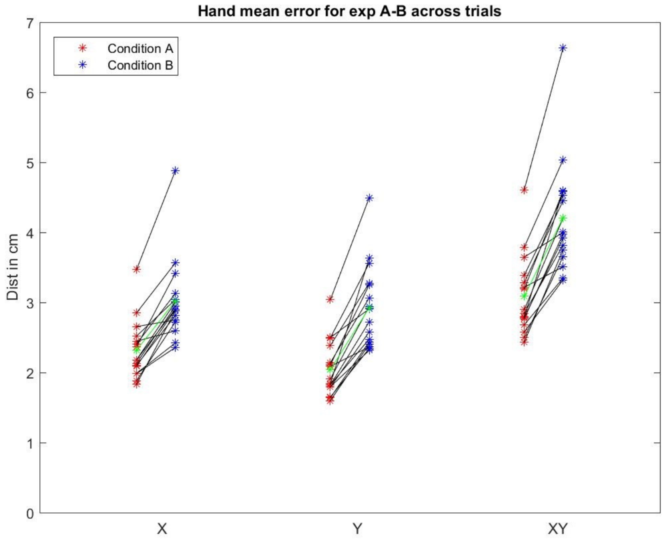

Figure 24: Hand error

In order to calculate this number, the absolute distance in X, Y and XY[14] is calculated for each step of time. The final value is the mean absolute distance across time. This means that for two steps of time, if the target is in (0,0), the hand is in (0,4) during one step on time and in (0,-2) during the other[15] : the mean Hand-Target error in Y is $\frac{|4|+|-2|}{2} = 3$.

We observe that during the condition B (blue stars), the error in X, Y and XY is greater ($p\text{-value}<0.01$) than in condition A (red stars). The average variability of each condition (represented in green) also tends to be greater in condition B (in blue) than in condition A (in red).

Once this is established, the directional component can be studied. Indeed, here we summarize a 2D behavior into 1 number (the average distance between the subject's hand and the target). The heatmap presented in figure 25 is a typical heatmap of the hand error.

---

[14] When the term XY is used it means the euclidian distance in 2 dimensions, which is $\sqrt{X^2 + Y^2}$.

[15] This is a hypothetical case to understand how the mean is calculated.

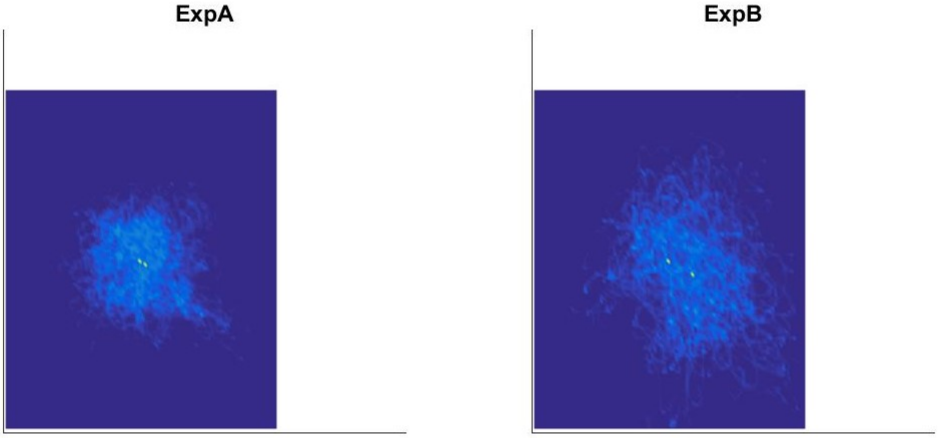

Figure 25: Typical heatmap of the Hand-Target distance. Subject 8.

This blue square has a 20cm side and the target as a center. Two brighter dots are: the representation of the target (in the center of the image) and the mean error (in the center of the cloud). The mean error has been calculated by approximating the cloud of dots by a 2D Gaussian's function.

If we summarize the heatmap in 2 parameters: one dot (the center of the cloud) and one ellipse (standard deviation in X and in Y), the 16 heatmaps can be represented on the same figure below :

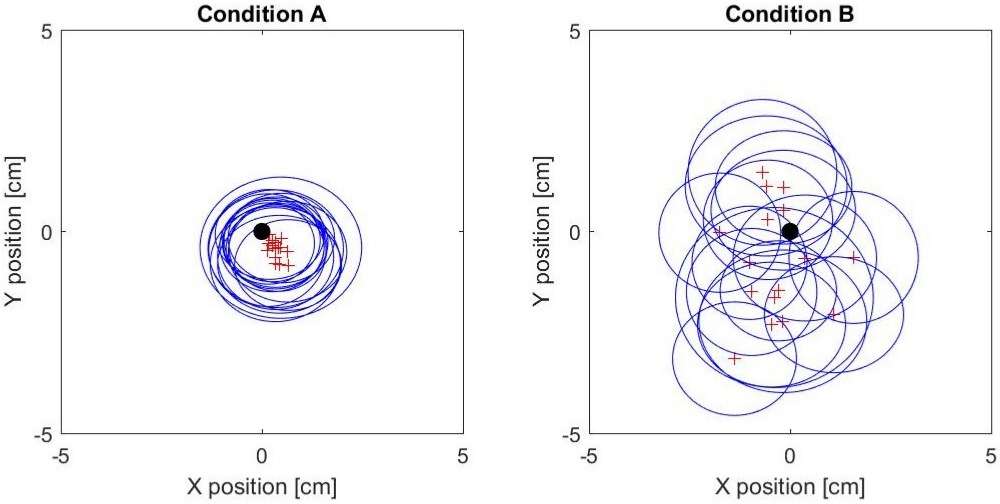

Figure 26: Sum up of all heatmaps of the hand error.

This heatmap explains the increase of the Hand-Target error of figure 24 by two different factors. The first is that the subject is far less precise without seeing his

---

[15] The standard deviation increases.

hand (p-value<0.01) and the second is that an offset is present. These two effects can be seen on figure 26.

The exact value of the data represented on figure 26 can be read in table 3 :

	Hand-Target Error [cm]							Hand-Target Standard deviation [cm]			
	Cond A			Cond B			Ration A/B [%]	Cond A		Cond B	
	X	Y	XY	X	Y	XY	XY	X	Y	X	Y
Sujet 1	0.2	-0.3	0.3	-1.7	0.0	1.7	17	2.3	2.0	3.0	3.0
Sujet 2	0.4	-0.4	0.5	-0.3	-1.5	1.5	33	2.4	2.0	2.9	2.5
Sujet 3	0.3	-0.4	0.5	-0.2	-2.2	2.2	23	3.4	2.9	4.2	3.5
Sujet 4	0.2	-0.1	0.2	-0.2	0.5	0.6	33	2.7	2.2	3.6	3.0
Sujet 5	0.7	-0.8	1.1	1.1	-2.1	2.3	47	2.7	2.3	3.5	2.9
Sujet 6	0.4	-0.4	0.6	-1.0	-0.8	1.3	46	2.4	2.2	2.9	2.8
Sujet 7	0.3	-0.8	0.9	-1.0	-1.5	1.8	50	3.2	2.9	3.2	3.2
Sujet 8	0.3	-0.3	0.4	1.6	-0.6	1.7	23	2.6	2.2	3.2	3.3
Sujet 9	0.5	-0.2	0.5	0.4	-0.7	0.8	62	2.6	2.2	3.6	3.1
Sujet 10	0.5	-0.4	0.6	-0.4	-1.6	1.7	36	4.0	3.5	4.9	4.5
Sujet 11	0.3	-0.2	0.3	-0.2	1.1	1.1	27	2.4	2.1	3.4	2.8
Sujet 12	0.3	-0.6	0.7	-0.6	1.1	1.3	54	2.9	2.6	4.0	3.5
Sujet 13	0.6	-0.5	0.8	-0.6	0.3	0.6	130	2.9	2.5	3.2	3.0
Sujet 14	0.4	-0.8	0.9	-0.5	-2.2	2.4	38	3.1	2.4	3.7	3.1
Sujet 15	0.3	-0.4	0.4	-1.4	-3.2	3.4	11	2.6	2.3	3.0	2.8
Sujet 16	0.1	-0.5	0.5	-0.7	1.5	1.6	31	2.9	2.8	3.7	3.6
MEAN	**0.4**	**-0.4**	**0.6**	**-0.4**	**-0.7**	**1.6**	**42**	**2.8**	**2.4**	**3.5**	**3.2**
SD	**0.2**	**0.2**	**0.2**	**0.8**	**1.4**	**0.7**	**27**	**0.4**	**0.4**	**0.5**	**0.5**

Table 3: Hand-Target error for conditions A and B

The X,Y and XY error in this table is the error of the mean Hand-Target distance. This means that for two step of time, if the target is in (0,0), the hand is in (0,4) during one step on time and in (0,-2) during the other : the mean Hand-Target error is $(\frac{0+0}{2}, \frac{4+(-2)}{2}) = (0, 1)$ and its Hand-Target error in Y is 1.

5.1.3 Hand-Target error in relative frame

The previous section (5.1.2), focused on the error in the absolute frame which means that the way the error was measured was to consider the vector from the target to the error from an upper point of view. This distance can be measured by placing a fixed camera above the plane and measuring the X and Y components for each step of time.

We suggest in this section to consider another point of view, one related to the movement of the target. To illustrate this point of view, let's suppose that the target and the hand are two vehicles that follow each other. One way to measure the error would be to sit in the lead vehicle (the target) and observe whether the second vehicle (the hand) is in front, behind, to the left or to the right of the first vehicle. This is called the position relative to the motion of the target and means that the vector depends on the direction of the target. This distance is the distance measured if we create a second frame that sticks to the target and has the same orientation. As shown in the figure 27, the relative error is only another measure of the previous Hand-Target error.

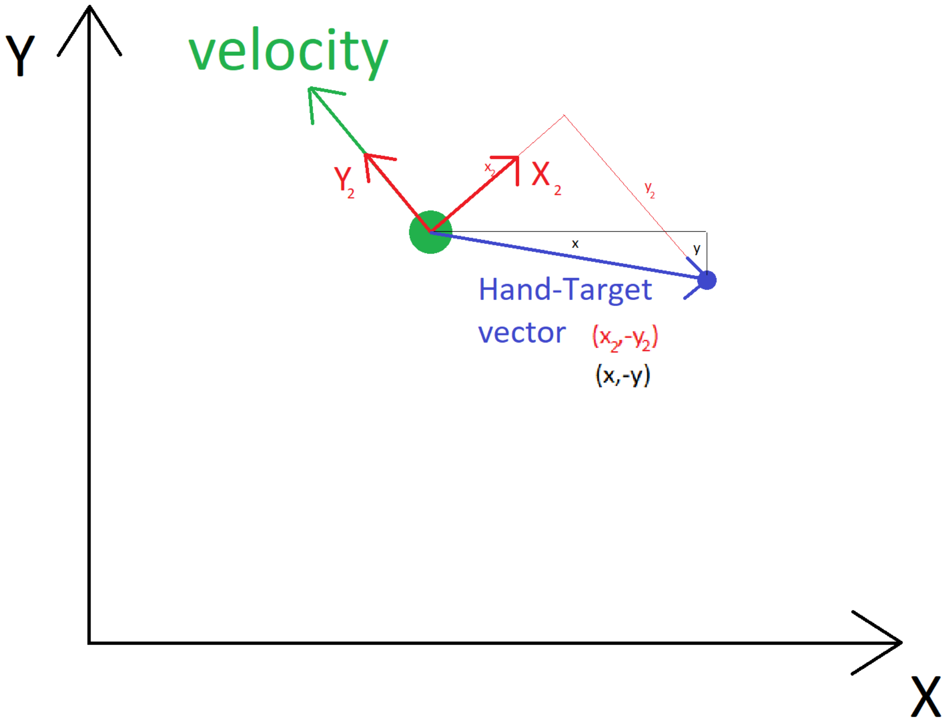

Figure 27: Two different points of view of the same distance: in black the Hand-Target in the absolute frame (as studied in section 5.1.2) and in red the relative Hand-Target error.

In this frame, a classical heatmap of the error during the 30 trials is illustrated in the figure 28 below.

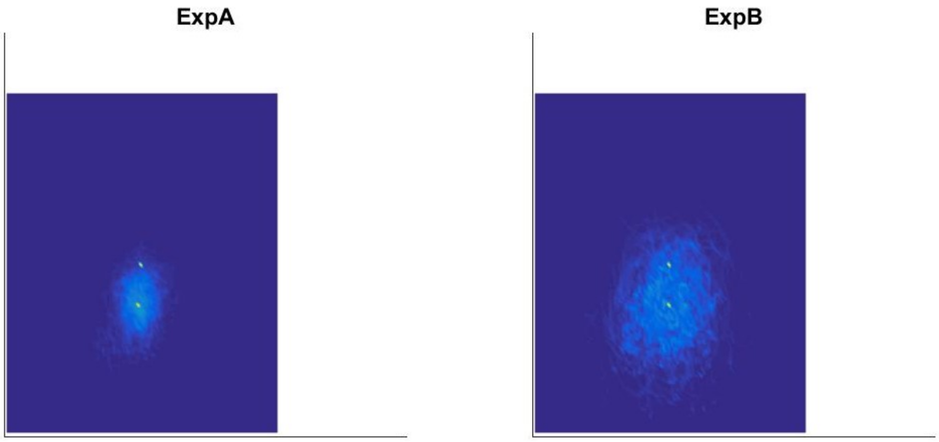

Figure 28: Typical heatmap of the Hand-Target distance in the relative frame. Subject 6.

As previously, the 16 heatmaps are summarized in one figure with 2 parameters per heatmap (the mean and the standard deviation).

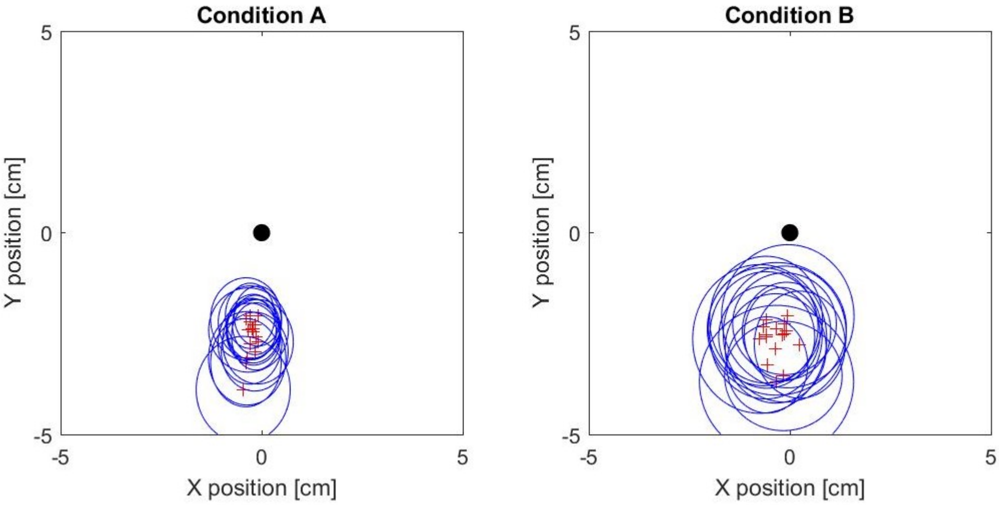

Figure 29: Sum up of all heatmaps of the hand error in relative frame

We can see in the figure 29 that the subject follows the target and is behind it at a certain distance (component Y), without any preference for left or right (component X).The distance seems the same in A or B (represented by the red crosses at equidistance of the black point) but the standard deviation increases (p-value<0.01) shown graphically by the diameters of the blue circles larger in condition B.

The precise data of the figure 29 is sum up in table 4.

	Hand-Target Error relative frame [cm]							Hand-Target Standard deviation [cm]			
	Cond A			Cond B			Ration A/B [%]	Cond A		Cond B	
	X	Y	XY	X	Y	XY	XY	X	Y	X	Y
Sujet 1	-0.1	-2.2	2.2	0.2	-2.9	2.9	76	1.2	1.7	2.3	2.7
Sujet 2	-0.2	-2.4	2.4	-0.2	-2.6	2.6	92	1.2	1.7	1.9	2.4
Sujet 3	-0.4	-3.2	3.2	-0.8	-2.8	2.9	110	2.0	2.4	3.3	3.8
Sujet 4	-0.1	-2.7	2.7	-0.5	-3.3	3.4	79	1.3	1.8	2.1	2.5
Sujet 5	-0.4	-2.2	2.3	-0.6	-2.7	2.7	84	1.8	2.2	2.8	3.2
Sujet 6	-0.3	-2.5	2.5	-0.1	-2.5	2.5	100	1.3	1.7	2.2	2.5
Sujet 7	-0.4	-3.3	3.3	-0.4	-3.0	3.0	110	1.8	2.3	2.5	2.8
Sujet 8	-0.2	-2.5	2.5	-0.6	-2.2	2.3	108	1.4	1.9	2.8	3.2
Sujet 9	-0.3	-2.3	2.3	-0.7	-2.5	2.5	92	1.6	2.0	2.7	3.0
Sujet 10	-0.5	-3.9	3.9	-0.5	-3.8	3.8	102	2.4	2.7	4.0	3.9
Sujet 11	-0.3	-2.2	2.2	-0.6	-2.7	2.7	81	1.3	1.8	2.4	2.7
Sujet 12	-0.3	-2.5	2.5	-0.4	-2.5	2.5	100	2.0	2.2	3.5	3.4
Sujet 13	-0.3	-2.8	2.8	-0.2	-2.4	2.4	117	1.6	2.1	2.6	2.6
Sujet 14	-0.1	-2.8	2.8	-0.2	-2.7	2.7	104	1.8	2.2	3.0	3.4
Sujet 15	-0.2	-2.6	2.6	-0.1	-2.3	2.3	114	1.4	1.8	3.2	3.6
Sujet 16	-0.2	-3.0	3.0	-0.2	-3.5	3.5	85	1.7	2.0	2.9	2.8
MEAN	**-0.3**	**-2.7**	**2.7**	**-0.4**	**-2.8**	**2.8**	**97**	**1.6**	**2.0**	**2.8**	**3.0**
SD	**0.1**	**0.5**	**0.5**	**0.3**	**0.5**	**0.6**	**13**	**0.3**	**0.3**	**0.6**	**0.5**

Table 4: Hand-Target error for conditions A and B in relative frame

5.1.4 Eye-Target error

In the study of Eye-Target distance, we find it important to recall that subjects were not instructed to follow the target and were willing to look where they wanted to.

First of all, as for the Hand-Target error, the mean distance is calculated for each subject[16]. This is shown in figure 30 below.

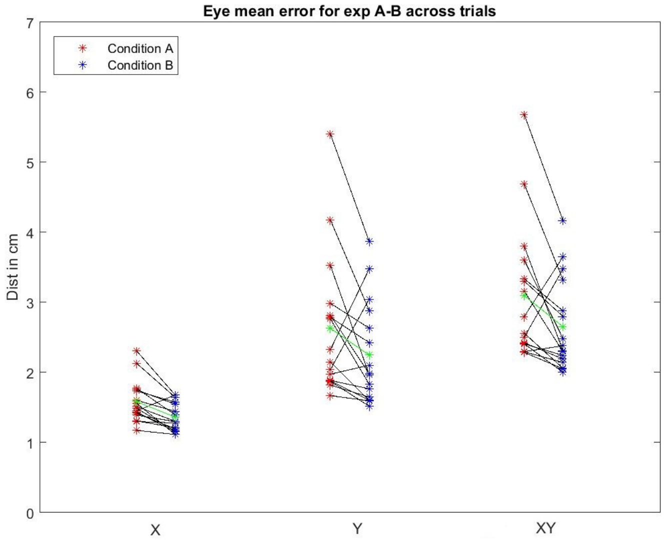

Figure 30: Eye-Target distance

It seems that the distance between the eye and the target is slightly lower during condition B. This is not a strong conclusion: the difference is little and not verified for every subject. This could be explained by considering that in condition A, the gaze is influenced by the presence of the hand. The eyes do not have to be focused only on the target but also on the hand which is not exactly at the same place. Anyhow, this effect is really small, there is no big difference between condition A and condition B in the Eye-Target distance.

5.2 Passive experiments

The instructions given to the subject for the passive experiment only concern the eye. Indeed, the subjects' hands are moved by the robot. The instruction given to the subjects is to look at the screen. In condition C, they have to follow visual feedback of their hand. In condition D, they have to follow the (imaginary) trajectory they assume their hand is making as the robot moves it.

---

[16] The mean of the absolute distance, so no direction taken in account.

5.2.1 Typical result

As the robot moves the handle, the hand and the target are always exactly at the same location during the passive experiment. The typical condition C is represented in figure 31.

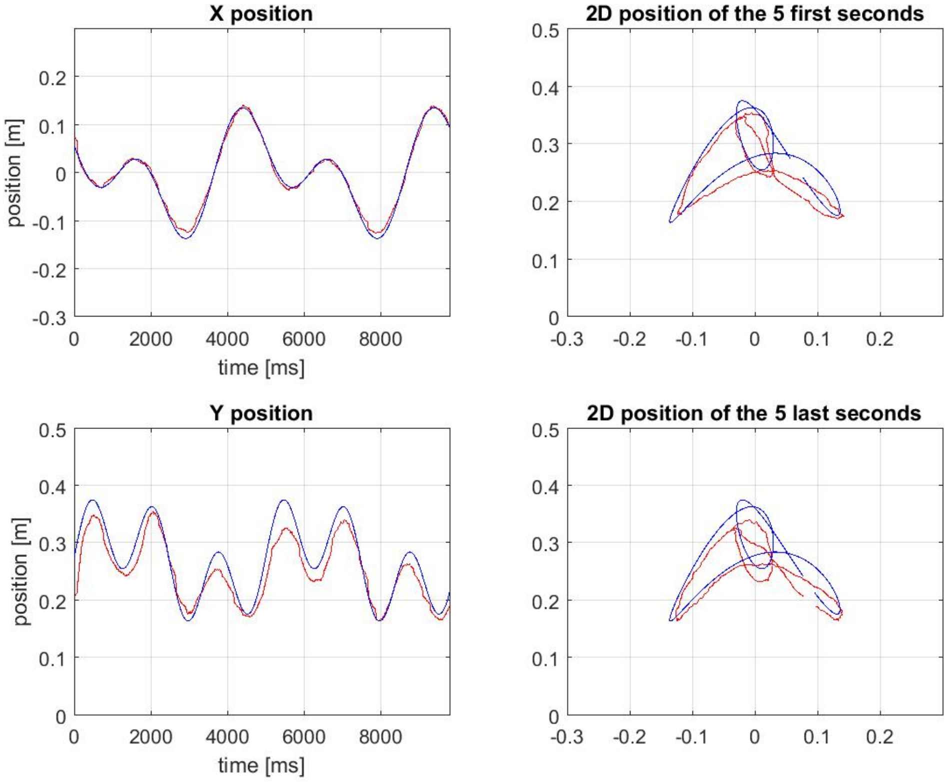

Figure 31: A typical trial of condition C. Here is subject 2 trial 90.

The condition C seems similar to the active condition but without any error in the hand movement. This is an obvious observation as the hand is directed by the robot. The trajectory of eye movement follows relatively well the visual feedback given by the moving hand as the subject can then focus essentially on this task.

The eye movement is really different during the D condition, see figure 32. We are discussing this observation in the following section.

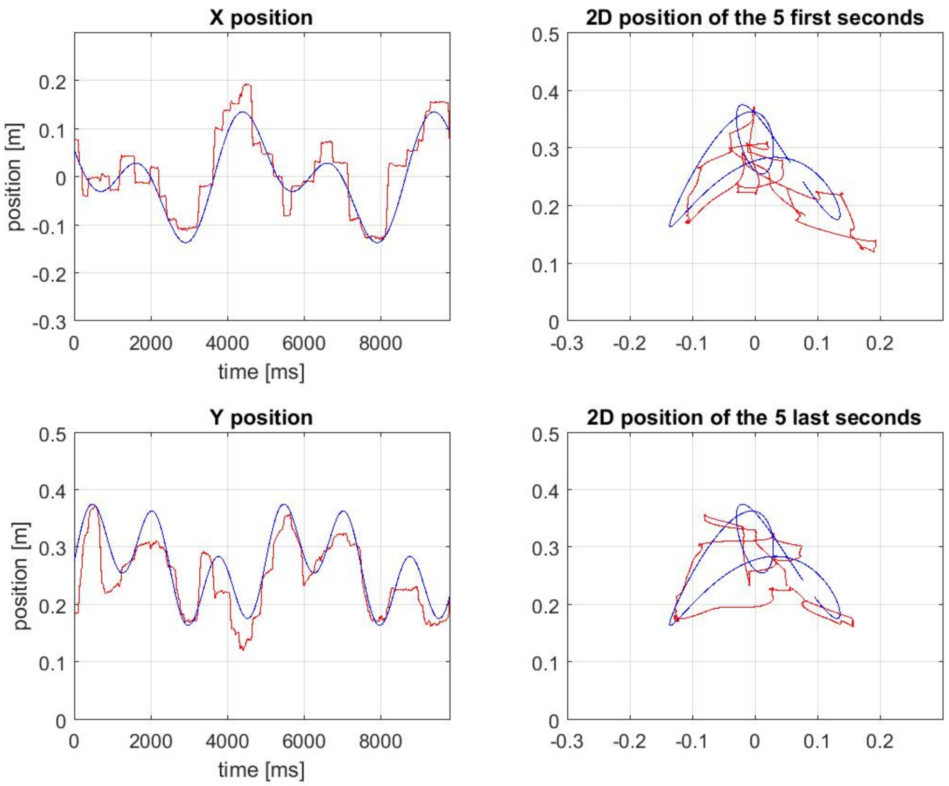

Figure 32: A typical trial of condition D. Here is subject 2 trial 120.

5.2.2 Eye-Target error

As for the active condition, before going into 2D representation or more detailed analysis, a first approach is to calculate the mean of the instantaneous distance between the eyes and the target.

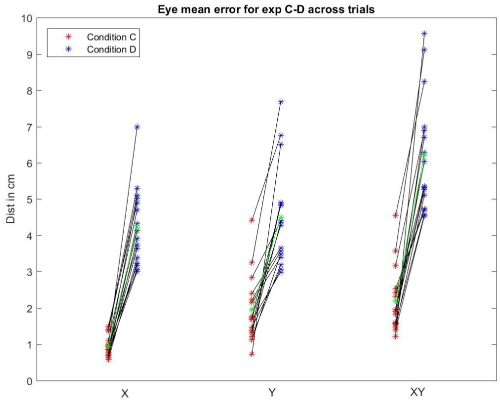

Figure 33: Eye error during condition C and D.

Figure 33 reflects the fact that the error is bigger (p-value<0.01) when the subject does not see his hand (condition D), which was expected.

The next analyze is to study if there is a directional effect. As the typical heatmap of the eye illustrates in figure 34, there is a directional component to the error.

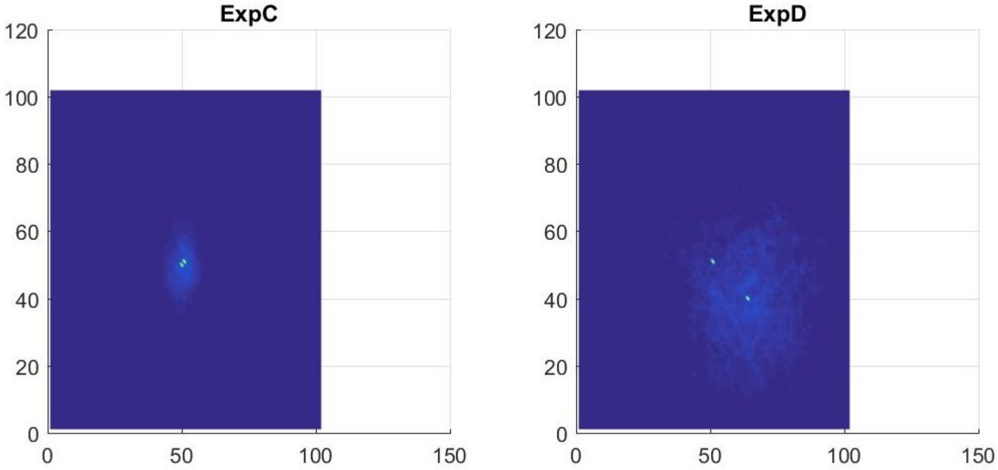

Figure 34: Typical heatmap of the relative eye position toward the target. Subject 11.

The results of the 16 subjects are shown in the figure 35 below.

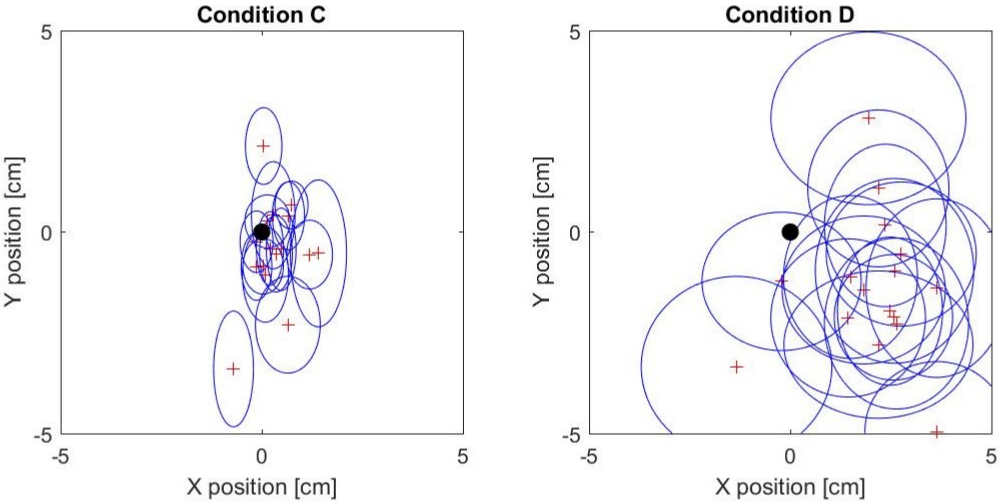

Figure 35: Sum up of all heatmaps of the eye error

We can see on figure 35 that the error in the graph on figure 33 seems to be due to two factors : a bigger constant offset and a larger standard deviation in D (p-value<0.01).

	Eye-Target Error [cm]						Eye-Target Standard deviation [cm]			
	Cond C			Cond D			Cond C		Cond D	
	X	Y	XY	X	Y	XY	X	Y	X	Y
Sujet 1	0.4	-0.5	0.6	1.4	-2.1	2.6	0.8	1.9	3.8	3.9
Sujet 2	0.2	-0.4	0.5	-0.2	-1.2	1.2	0.7	1.8	4	3.4
Sujet 3	1.4	-0.5	1.5	3.6	-5.0	6.2	1.4	3.6	3.6	3.5
Sujet 4	0.0	2.1	2.1	2.5	-2.0	3.2	0.8	1.8	2.5	3.4
Sujet 5	0.7	0.4	0.8	2.4	0.2	2.4	0.8	1.7	3.0	4.0
Sujet 6	0.3	0.4	0.5	1.8	-1.4	2.3	1.1	2.7	4.1	3.7
Sujet 7	0.1	-1.1	1.1	1.5	-1.1	1.9	1.1	2.4	3.3	4.0
Sujet 8	-0.7	-3.4	3.5	-1.3	-3.3	3.6	1.3	3.3	4.7	5.0
Sujet 9	0.0	-0.9	0.9	2.6	-1.0	2.8	1.0	1.4	3.9	4.6
Sujet 10	1.2	-0.6	1.3	3.6	-1.4	3.9	1.5	2.1	3.7	4.7
Sujet 11	-0.1	-0.2	0.3	2.6	-2.1	3.3	0.8	1.5	2.9	3.1
Sujet 12	-0.1	-0.9	0.9	2.6	-2.3	3.5	0.8	1.7	3.6	4.2
Sujet 13	0.6	-2.3	2.4	2.2	-2.8	3.6	1.7	2.4	4.7	3.6
Sujet 14	0.1	0.3	0.3	1.9	2.8	3.4	1.1	1.3	4.8	4.3
Sujet 15	0.7	0.7	1.0	2.2	1.1	2.4	0.8	1.2	3.5	3.9
Sujet 16	0.5	-0.4	0.6	2.8	-0.5	2.8	0.7	2.0	3.7	3.6
MEAN	**0.3**	**-0.5**	**1.1**	**2.0**	**-1.4**	**3.1**	**1.0**	**2.1**	**3.7**	**3.9**
SD	**0.5**	**1.2**	**0.9**	**1.3**	**1.8**	**1.1**	**0.3**	**0.7**	**0.6**	**0.5**

Table 5: Eye-Target error for conditions C and D

Position is not the only important component of eye movement. As we have seen in previous sections, the functioning of the eye is composed of two types of movement: the smooth pursuit and the saccade.

If we only look at the number of saccades it seems that the way of moving is the same because the number of saccades is the same through the four conditions as shown in figure 36.

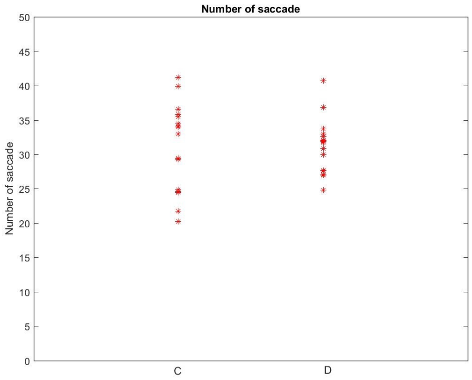

Figure 36: Number of saccades by condition

But if we look more closely at the characteristics of the saccades, we find that they are ultimately different. As represented in figures 37 and 38, the saccades are longer and bigger (both with p-value<0.01) during the condition D (black screen) thant when there is something on the screen to follow (target or both target and Hand-feedback).

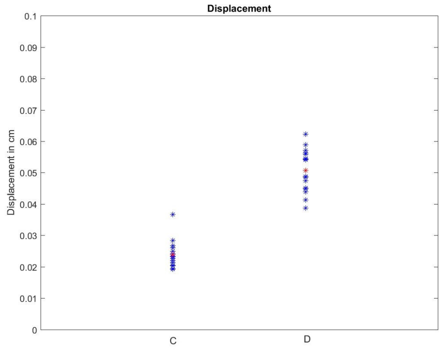

Figure 37: Displacement of saccades

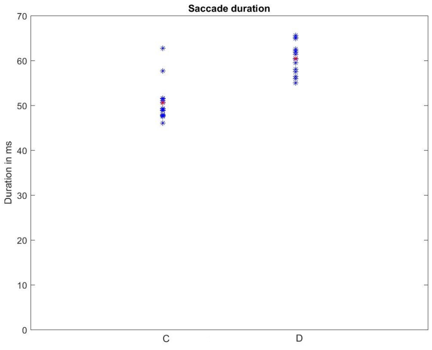

Figure 38: Duration of saccades

The fact that the saccades mode is more used during the condition D is comfirmed by the following figures (39, 40, 41 and 42) showing the total distance travelled by the eyes either in smooth pursuit or in saccades.

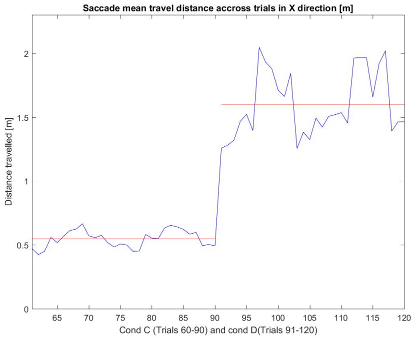

Figure 39: Saccade total distance in X

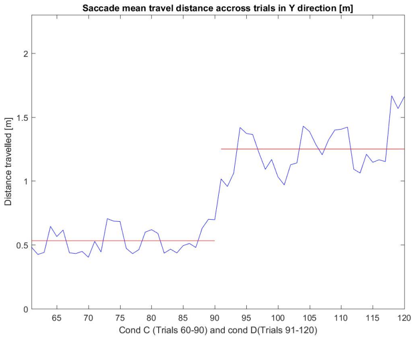

Figure 40: Saccade total distance in Y

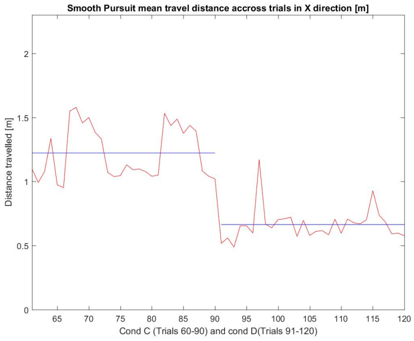

Figure 41: Smooth pursuit total distance in X

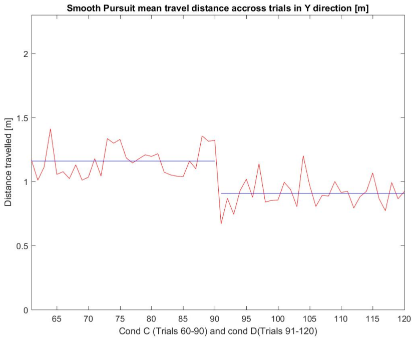

Figure 42: Smooth pursuit total distance in Y

As shown in table 6 (which details the information from the previous figures) the ratio of smooth pursuit over saccades is about 70% when there is a target to track and drop (to 40% in Y and 30% in X) for condition D.

Saccades-SP ratio										
	X					Y				
	Sacc [m]	SP [m]	Total dist [m]	Sacc [%]	SP [%]	Sacc [m]	SP [m]	Total dist [m]	Sacc [%]	SP [%]
C	0.547	1.223	1.770	30.9	69.1	0.532	1.160	1.692	31.4	68.6
D	1.600	0.664	2.264	70.7	29.3	1.250	0.907	2.157	58.0	42.0

Table 6: Ratio of smooth pursuit and saccades

5.3 Learning process

Since the subjects perform the same task over and over again, we asked ourselves if we could observe a learning effect. In the case of our study, we could not observe any change in the results of the different subjects through the trials, regardless of the condition. Even for the two non-naïve subjects described in section 2.2, the data collected do not reveal any learning effects during the experiment.

The figures 43 and 44 show the fact the the subject does not learn for conditions A and B as the Hand-Target distance stays the same, and similar results are obtained for the Eye-Target distance for conditions C and D.

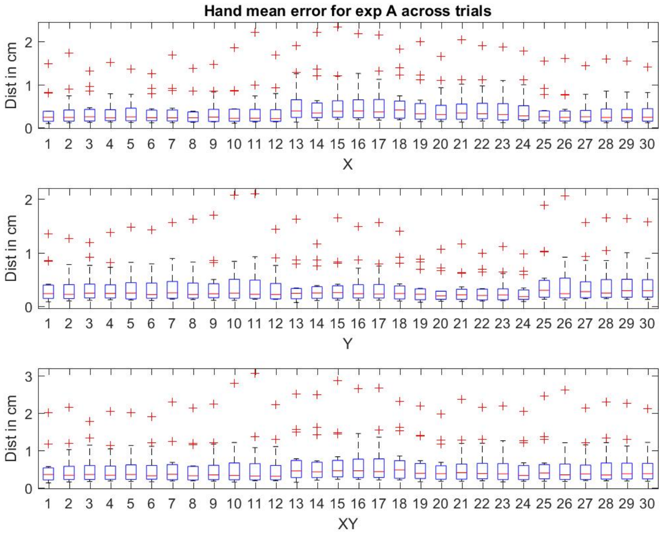

Figure 43: Hand-Target errors through the trials in condition A

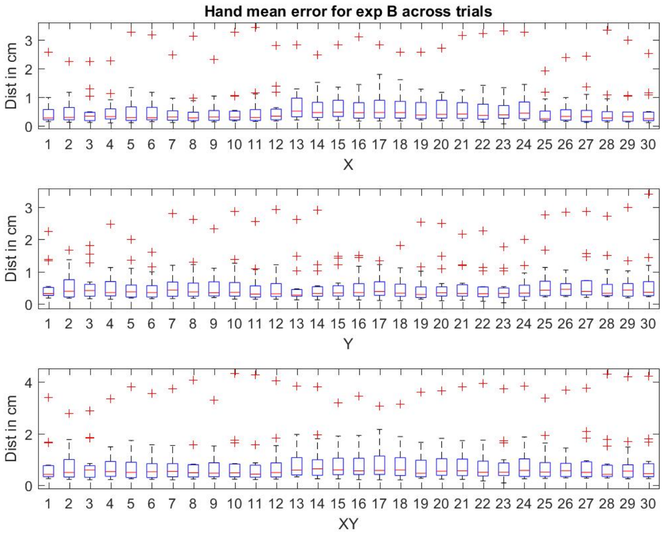

Figure 44: Hand-Target errors through the trials in condition B

These observations may be due to several factors. One is that the experience does not encourage the subject to improve. Indeed, no bonus points or rewards are granted in case of improvement. The second factor is the fact that the trajectories are really complicated to memorize, especially since the subject does not have a global image of the trajectory but only of its instantaneous position. A third factor that must be considered in conditions B and D is that the subject does not receive feedback on how he or she performs the task (good or bad).

6 Discussion

6.1 The results in a nutshell

Here under, a rapid sum up of the different results shown in detail in section 5.

6.1.1 Active

When studying the hand error, the first conclusion is that the sum of all instantaneous errors is greater in condition B than A (without taking into account the direction, just summing up the distances).

Then to go further in the analyze and to study the 2D behavior, we create some heatmaps that represented the error in a XY plane. The error was distributed as a 2D gaussian functions, the mean errors (in X and Y) and standard deviations (also in X and Y) of the gaussian shape have been calculated for each subject. For condition A, the mean errors are small and all directed toward the same direction (below and left). For condition B the mean errors were bigger and spread all around the (0,0) coordinate. The standard deviation was significantly bigger in B.

To have another point of view than the one in the fixed frame XY, it seemed interesting to study the error in a relative frame which is stuck to the velocity vector. We then got new heatmaps, which were also 2D gaussian functions but with different mean and standard deviations. In there case their is no significant difference between the mean errors of condition A and B. They are both, and for all subjects, situated a few centimetres negative in Y and no significant preference for the X coordinate. As for the previous heatmap, the standard deviation is significantly bigger in condition B than in condition A.

Even if there was no instruction about the gaze[17], a rapid study showed that the error in absolute value in slightly lower in condition B than A.

6.1.2 Passive

During the passive condition we study the Eye-Target distance. The first observation is that, as the Hand-Target between condition A and condition B, the sum of all instantaneous Eye-Target error is greater in condition D than in condition C (without taking into account the direction, just summing up the distances).

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[17] Which implies that the results are less relevant because the subject was free to adopt any technique in order to achieve his real goal : the precision in the hand movement.

The further analysis as for the Hand-Target distance is to study the problem in two dimensions to take into account the directional effects. In this analysis we can conclude that the error seen in the first approach is due to two effects in condition D : the eye has an offset and the standard deviation is bigger.

Not only the path and the mean error are different but the way the eye moves also changes between condition C and D. Even if the number of saccades is the same, the duration and the amplitude of the saccades are significantly bigger during condition D. This induces that the ratio between path in smooth pursuit and path in saccade is much bigger in condition D.

6.1.3 Learning process

Finally we observe no learning effect at all, in any condition or for any trajectory.

6.2 Reliability of the data

6.2.1 Subjects

First of all, 16 subjects are enough to make analysis and try to understand how the body reacts and thus develop theory about internal models, but it's weak to ensure with a 100% security that the measures and the conclusions are entirely true for the world wide population.

A good example of this is that every subjects were right handed. This was done on purpose so that it does not affect our results but therefore narrow the validity range of our results. One possible thing to do would be to reiterate the same experiment on left-handed people to see if the conclusion developed here are still valuable.

Another thing which is important to mention is that each subject came only once and did every measures on the same day. This means that there is no way to say if the results are dependent on the actual physical and mental state of the subject. There is no way to tell if the fatigue, external stress, hour of the day, physical form or any external parameter has an effect or not on the results.

6.2.2 Recorded data

As for any experiment in sciences, the data are never 100% reliable. It's interesting to discuss the parameters that are more reliable and those who are less.

The target and the hand position are highly reliable. Indeed, first and foremost, they are based on really reliable technologies which are known, used and mastered for a long time (matlab programming, motor control and screen displaying). Secondly, a time-to-time feedback is sometimes shown which ensures that the robot and the program respond normally. Finally, the recorded result seems coherent.

A parameter that is less reliable is the eye position. Eye tracking is based on more complicated technology. As said in section 2.1.2, in order to compute the position of the gaze on the screen, the first thing needed is the position of the eye relatively to the head. This technology is less stable and this for several reasons. First, the eye tracker has some difficulties to track correctly the pupil. This error, which can be seen on the time-to-time feedback displayed on the screen, can be due to several parameters like: the shape of the subject's eye, the lighting, the color of the eye, big eyelashes... Moreover, the subject systematically moves slightly his head during the experiment. This makes the relative position of the eye less correct, even if there is a marker on the cheek to minimize this error.

As explained in section 4, the signal has been treated in a post-experiment process. Bad and incoherent data have been deleted and four measures have been done during the experiment in order to minimize the errors due to the length of the experiment. Even with this post-experiment treatment, the eye data are not perfect.

6.3 Internal model

In our study, we identified four conditions (A, B, C and D) in two modes (active and passive) in order to discuss the different internal models used in these different tasks. The figures below illustrate how, in our study, the internal models can be represented according to the task requested and the perceived sensory feedback.

Under conditions A and B the whole scheme is at work (figure 45). However, in condition B, there is no visual feedback from the hand that can be used by the internal model.

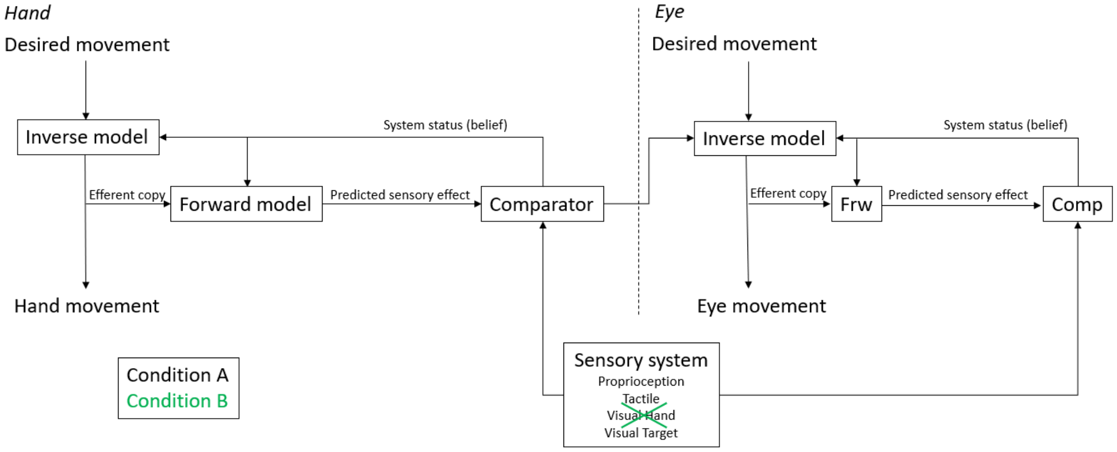

Figure 45: Internal model in conditions A and B

Under conditions C and D (figure 46), as hand movement is not desired, the reverse model does not send an efferent copy to the forward model, which cannot be used either. The internal model of the hand is ignored and only the internal model of the eye is used. In condition D, as in B, there is no integrable visual feedback and only the proprioception of the hand is used to provide information related to the model.

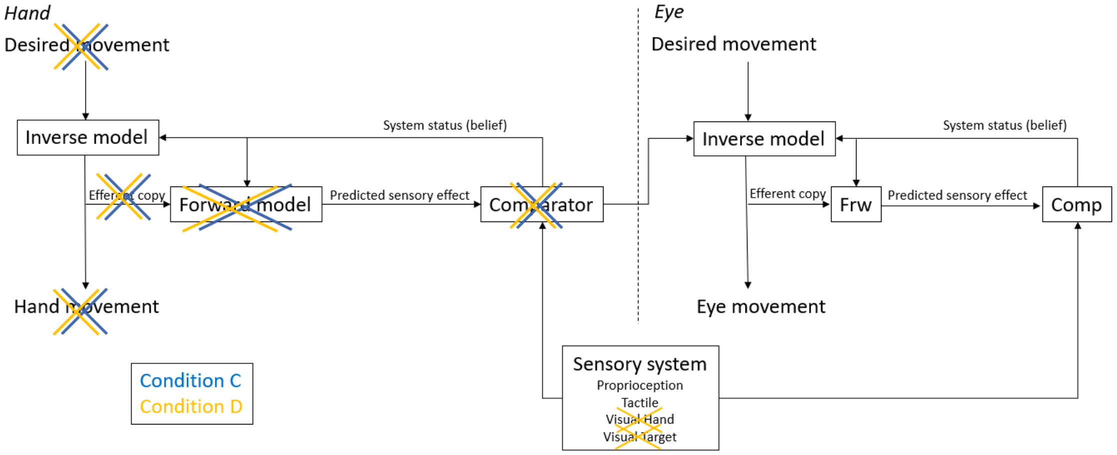

Figure 46: Internal model in conditions C and D

6.4 Areas of improvement

6.4.1 Asymmetry

As said previously the experiment was only concerning right handed subjects who used their dominant hand. It would be possible to go further in the data collection by doing the same experiment with three other categories : right handed with their non-dominant hand and left handed with both their dominant and non-dominant hand. As one of the main topics discussed in this work is the position of the hand relative to a target, this could bring a deeper comprehension of the mechanisms. This could also show if both left and right handed behave the same way or not.

Another point of view would be to do the same experiment (ideally with the same subjects) but with the trajectories going in the opposite direction. It could allow to study more in-depth the influence of the velocity.

6.4.2 Going further in the internal model

The main purpose of the work was to analyze and understand the internal model of the eye-hand coordination. With this goal, one experiment with four conditions has been developed. These four conditions allow us to understand the role and the importance of the vision (with the hand feedback present or not) and the role of the afferent or efferent message of the arm movement (with active and passive conditions). Here are some suggestions to complete this study, some of them are feasible, others may encounter technological boundaries.

First, what would have been interesting is tracking the eye movement to see where and how the eye move without any information from the arm. Indeed, in this experiment the am was always involved and able to send afferent or efferent message to the eye. A condition without any message could be interesting.

An other idea for future studies would be to instruct about closing your eyes rather than looking at a black screen when it is asked to follow an imaginary trajectory with your eyes (condition D). Indeed, this would completely block the presence of possible visual afferences, and make the trajectory more fluid thanks to the absence of dust and other irregularities that capture the subject's gaze while he is looking at a black screen. However, it should be noted that this is a theoretical suggestion as, in practice, it is not feasible to track the visual trajectory that a subject exercises with his eyes closed.

A last suggestion would be to ask the subject to follow a random trajectory (to use an efferent copy), without him seeing his hands, and to ask him to follow his trajectory with his gaze. This would allow us to compare accuracy errors between a predicted and unpredicted (condition D) trajectory without visual feedback. However, the randomness of the predicted trajectory of each subject can complicate the comparison between the different subjects.

6.4.3 Going further in the analysis

This work is a one year project, no matter how interesting the results are, the analysis had to be stopped in order to finish the thesis in time. As said previously, the hand error is dependent on the direction of the target's velocity. Two interesting analysis to add would have been : to compare the hand error to the velocity amplitude (not only direction) and to compare the hand velocity to the target velocity (amplitude and direction). Finally, this could also be done for the Eye-Target distance.

7 Conclusion

In conclusion, our work aimed to study oculomotor synchronization in dynamic motion. Through our protocol with four conditions and using the KINARM robot, we collected and analyzed data from sixteen volunteer participants and extracted the information necessary to understand better this type of coordination.

The results presented in our work show first of all that the visual contribution is always an advantage in the precision of the movements performed by the subject. Indeed, and this seems quite logical to us, when these benefit from visual afferences, the movements performed are more accurate.

A second element that our results show is that the relationship between the duration of the saccades and that one of the smooth pursuit is, as expected, more important in passive conditions without visual feedback (condition D). This is because the eye is trying to establish a trajectory without really knowing it.

Thirdly, our results could not show the presence of a possible learning effect through the different tasks.

In addition, our dynamic study did not allow us to identify any similarities with the tracking mechanism used in static conditions. We believe that these conditions could be underpinned by different operations.

Finally, we draw our attention to the importance of the framework chosen to study the data. Indeed, depending on how we consider the latter (in terms of point of view), the observations may differ. In our case, it seemed more appropriate to study these phenomena in a relative frame.

To conclude, the various results we have obtained make it possible, in all modesty, to advance research on the study of oculomotor coordination in dynamic conditions. By confirming or not supporting the data in the scientific literature on the subject, by suggesting avenues for reflection and suggestions for future studies on the mechanisms underlying our movements, our research makes it possible to develop knowledge in these fields, which are essential in understanding how human beings work.

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