École polytechnique de Louvain

Visuo-haptic coordination in tracking tasks

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Abstract

We regularly coordinate our eyes and our hands movements in our daily tasks. While these tasks seem obvious to us, in reality a complex model is hidden behind these. Thus, the visual and the haptic systems are analysed in several tracking tasks. In that respect, the role of the vision in the hand tracking task, the role of the hand proprioception in the eye tracking task, the role of the trajectory predictability and the role of the hand used are studied. For this purpose, a protocol was realised with the KINARM robot and some volunteers. The results support observations from the scientific literature and contribute to the understanding of the different roles of the elements constituting the internal model for the coordination between the hands and the eyes.

Contents

1 Introduction

During our day (Figure 1), we regularly coordinate our eyes and hands [1] whether to write, draw, paint, cook, garden, use a computer mouse, grab objects... We carry out these actions easily without realising them, it seems natural, but in reality a complex model is hidden behind these [2]. Some neural mechanisms contribute to collect data and coordinate movements. There are the visual system with eye and the proprioception which allows to be aware of body member's positions or movements through muscle contractions. An other system is the haptic perception thank to the skin during active exploration of surfaces. By combining these three systems, it is possible to make precise movements. Understanding these systems of coordination more precisely could help in various fields. As an example for rehabilitation after an accident or a stroke [3], for diagnostics, for prosthetic devices or robotics [4], for predictive models, for training of mastering skills... To study these systems, data from thirteen subjects were collected during a protocol of three hours. The role of vision in hand tracking task is studied during a session of active movements and the role of the hand proprioception in eye tracking task with passive movements. Two different trajectories (straight line and curve) are compared as well as the influence of the hand used (right or left). To start this report, a brief state of the art is realised to explain theories about concepts that are necessary to know for a better understanding. An explanation will follow on methods used as the protocol, subjects and materials. Before analysing results and discussing about them, a description of data processing will be done. It is important to note that this thesis is an extension of the master thesis of L. Martin Y Muyshondt and E. Vansnick ("Studying dynamic tracking by the hand and the eyes" [5]) and that some sections are inspired by it as well as by the doctoral thesis of J. Mathew ("Investigating predictive mechanisms underlying eye-hand coordination" [6]).

Figure 1: Examples of actions with eye and hand coordination.

2 State of the art

Before presenting the coordination between eyes and hands, we separate the two systems. Firstly we describe the eye movement follow by the hand motor system. Finally, a brief description of the internal model for the eye-hand coordination will be described.

2.1 Eye movement

The principal organ of visual system is the eye. So a brief description of this one is done. In figure 2, the several elements that composed the human eye can be observed. The cornea is a transparent convex membrane and is the first refractive element of the eye [7]. With cornea, the lens cover by this one converge the light on the retina [8]. The intensity of light entering in the eye is modulate by the contraction or not of the iris (colored part of the eyes). The black hole left by the iris that we can see is the pupil. Thanks to the lens capsules (posterior and anterior) that we can observe on the figure, the lens is kept in place and is connected to the ciliary muscles. The ciliary muscles contract or lengthen to change the curvature of the lens and to change the focus of the convergence of light. The retina is the back of the eye where the photoreceptors are located [9]. When light hits these photoreceptors, some electro-chemical signals are sent to the brain to be processed. This information is sent through the optic nerve. The vitreous humour allows to keep in place the retina, it is a clear gel that fills the space between the lens and the retina. Finally, on this figure 2, we can observe the macula which is the zone of retina in the axis of the pupil. This macula also named the fovea is the area responsible for the most precise diurnal vision thanks to a large cone cells concentration [10]. This characteristic is very important to understand eye movement because when we observe something we focus the centre of interest of the gaze on fovea. Indeed, outside this fovea, the gaze is blurred with less details.

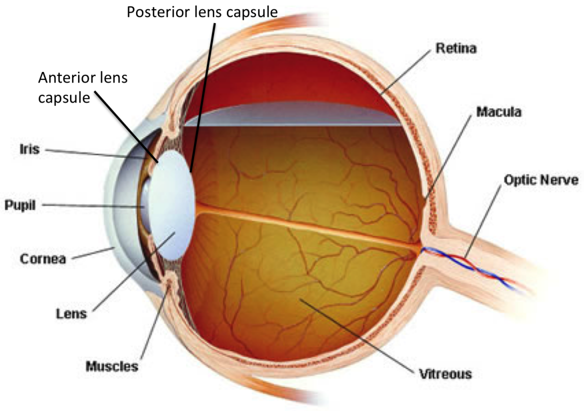

Figure 2: Diagram of the human eye [11].

The eye therefore needs to move and this can be done thanks to 3 pairs of oculomotor muscles [12]. First pair for abduction and adduction (around the z-axis), the second around x-axis for elevation and depression and the last one for torsion wich is necessary when you tilt your head [10]. During this thesis, we analyse fixational eye movements with two types of gaze shifting (saccades and smooth pursuits) in opposition to gaze stabilizing (vestibulo-ocular reflex and optokinetic reflex). If we have the impression of seeing perfectly in a large field of vision, it is because of the number of pictures that the visual system sends to the brain, approximately 12 frames per second (12 Hz). Like this, the brain considers the previous information from both eyes and environment to build a more precise picture. Analyzing eye tracking, more details about saccade and smooth pursuit are provided in these follow sub-subsections.

2.1.1 Saccade

A saccade is a quick movement like a jump between two points. A saccade is realised when we change of target focus [13]. For example, when you walk down the street, we can observe the person coming in front of us on the sidewalk and quickly change our focus to the dog barking accross the road. Another type of saccade is the "catch-up saccade" [14] that we realise when a target moves too fast (exceed 30°/sec) and that it is no longer possible to track in smooth pursuit (see next type movement). It is a non-adaptive movement [6] because when the decision is taken to do a saccade, the information takes by eyes between this decision and the end of the saccade cannot change the amplitude or the end position of this one. Only information received at least 70 ms before the initiation are considered for the saccade. Moreover during a saccade, a lot of information is lost because of the speed of the movement [15]. There are two types of "catch-up saccade", the forward saccade when the direction of the saccade is the same that the previous smooth eye pursuit or the reverse saccade with an opposite direction [16].

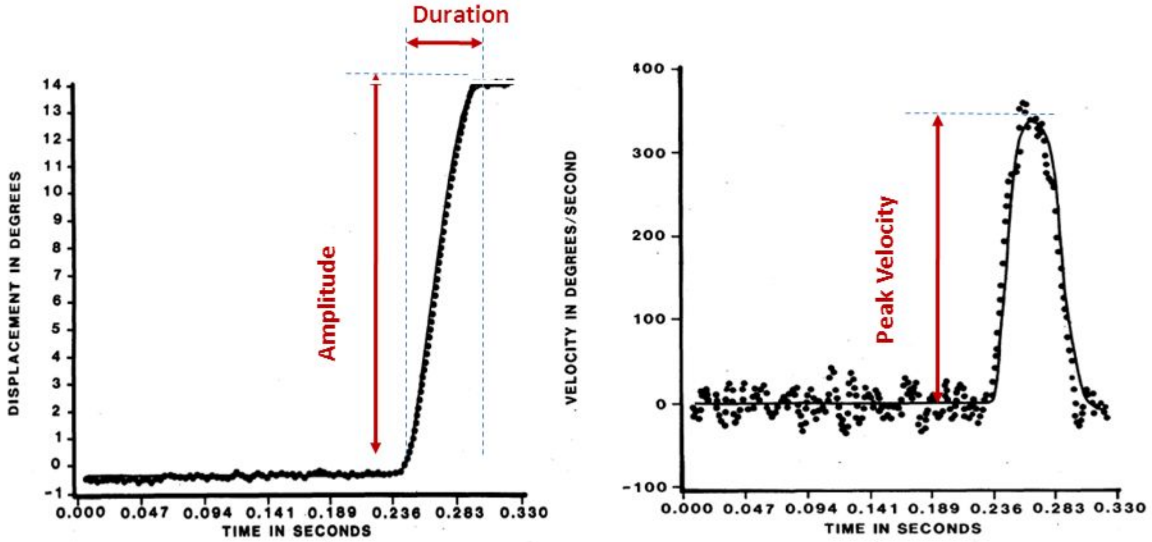

Figure 3: Representation 1D of a saccade with its different parameters [17]. The saccade is in the left graph, the eye position in solid black line and eye velocity with a peak is in the right figure [18].

On the figure 3, some important parameters of saccade are described. The position jump in one dimension can be observed in the left graph, it is the saccade. The amplitude is the travelled distance between the starting and final point while the duration (average of 20-80 ms) is the time taken to complete the eye movement [19]. An other parameter is the gain which is a ratio between amplitude and target's movement. In the right graph, the velocity reaches a peak during a saccade. A latency of approximately 200-250 ms is necessary to estimate the appropriate eye-target error after stimulus occurrence (time 0) [20]. For a more predictable marker and with training, this latency can be smaller (80-120 ms) [21].

2.1.2 Smooth pursuit

The second type of eye movement is the smooth pursuit when the trajectory of the target is more predictable and its velocity does not exceed 30°/s [15]. The goal of this pursuit is to keep the target on the fovea. One more time, before the ignition phase (Figure 4), there is a latency of approximately 100 ms from the first visual information (stimulus) on the target and the decision to begin smooth pursuit. Due to the eye system delay, the ignition or initiation phase corresponds to an open loop [19]. In this open loop, the initial acceleration (after 100 ms) is always a constant during 20 ms and during the next 80 ms there is an adaptation of the velocity and position of the gaze. The peak of velocity is at the end of the open loop. Therefore the maintenance phase can start with a closed loop whose role is to adapt the velocity of eye to stay focus on the target. It is possible to observe that during this phase, the velocity oscillates around the real speed of the target.

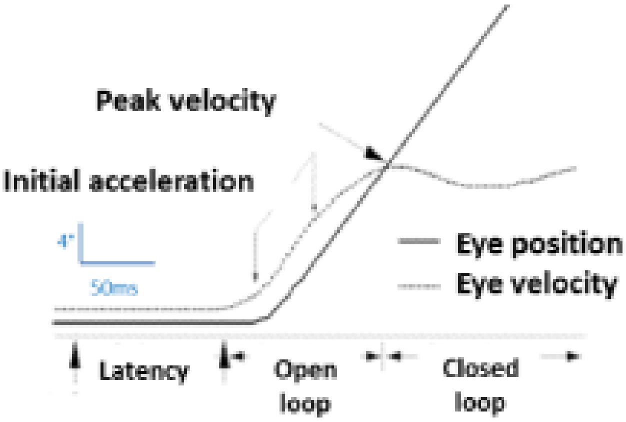

Figure 4: Representation 1D of a smooth pursuit with its different parameters [19] [5]. The eye position on the target trajectory in solid black line and eye velocity in dotted black.

2.1.3 Tracking with smooth pursuits and saccades

In the previous example of smooth pursuit (Figure 4), the trajectory of the target is very easy to anticipate with its constant velocity. In figure 5, the trajectory is less predictable and we observe that the smooth pursuit adapt the velocity to keep the fovea on the target but sometime it is not possible and it is necessary to make "catch-up saccade" to correct eye-target position error [15].

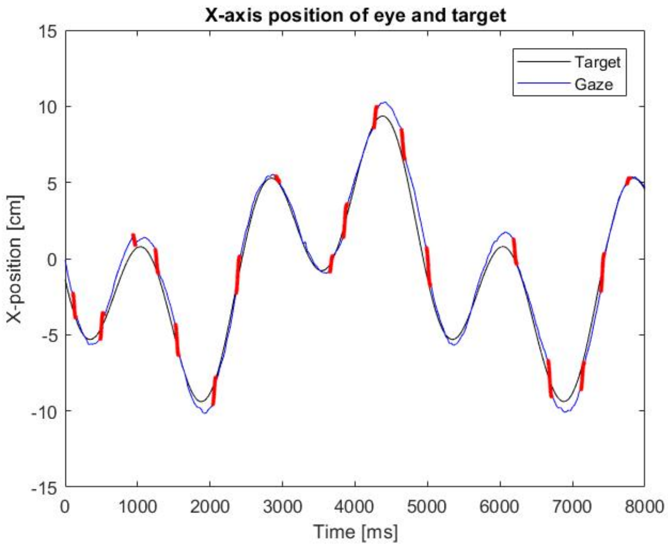

Figure 5: Eye position during eye tracking with a passive movement. In black, the target position and in blue smooth pursuit of eye with "catch-up saccade" in red to reduce eye-target error.

2.2 Hand movement

As mentioned in the introduction to manipulate an object with the hand, we need visual, proprioceptic and haptic information. In addition to the visual feedback, we can learn more about the object with the hand [22] as the weight, the surface, roughness, coefficient of friction... Firstly when we touch the surface of the object some information are sent to brain by tactile sensors (tactical kinesthetic surface) to prevent contact with it, to adapt grip force if it is slippery or to adjust properly control of the hand. Then muscle spindles and Golgi tendon organs are the proprioceptor for the proprioception and bring details about the spatial position (relative to the body) of the hand and arm thanks to the tension, length and joint angle of muscles.

Only continuous movements of hand tracking will be analysed in this thesis that are long and slow movements. During these movements, the hand trajectories are regulated. However there are also discrete hand movements like pointing, reaching or grasping that are short and fast [6].

Visual and proprioceptive information are used along the path at each time to plan motor signals [6] [23]. With the combination of these two inputs, we continuously know the current position of the hand.

The visual feedback gives an interpretation of the spatial environment (extrinsic information) to plan the way up to the visual target. Moreover during the movement, visual information allows to correct the online position errors (also for the end of reaching movements) [24]. Therefore, an inaccuracy of the hand movement is observed when there is a delay of the visual feedback [25].

Then proprioceptive feedback is more for the planning of motor commands thanks to intrinsic information [6] [26]. The proprioception is also for the control of ongoing movements [27]. Indeed, if the proprioception is disturbed, it is observed that there are some path variability in the later stages of voluntary movements [28]. Furthermore, some problems of inaccuracy movement control are observed in animals with a lack of proprioception (artificial removal) [29] and in deafferented patients [30]. This is especially true for movements of the hand with no visual feedback because it is shown by another study [31] that it is possible for people with a deficit of proprioception to perform accurate movements with hand vision [32]. It is also observed that the accuracy of proprioception is similar for the right and left hand [33]. To know spatial position of limb, a prediction of the future and expected posture is given by efferent information of proprioception while related information give a feedback of posture with a delay [34]. The information during the movement is used to update the internal model of the limb dynamics, which is then used to program the motor commands [35]. For a grasping activity, muscles length and joint change along the movement and give proprioceptive information to adapt the trajectory according to its kinematic [36].

Active (self-move of the hand) and passive (externally-move of the hand) movements are done in this thesis and it is observed that the accuracy (position of the limb) of active movements during adaptive capacities is better than passive movements [37]. This would be explained by the fact that the muscles are activated voluntarily and activates more muscle spindles.

2.3 Eye-Hand coordination

For movements, it is necessary to control the eyes and one or both hands simultaneously. This is not two independent systems because there is a coordination control between them (eye-hand coordination). This coordination between hand motor system and eye motor system is necessary and complex [1]. The coupling of the two system depend of the task. For example, the vision for action consists to share the signals send to the eye with hands or conversely action for vision where the signals of hands are shared with eyes [5] [6].

In accordance with literature [38], the accuracy of eye tracking is better when the target is moved by the subject himself (self-moved target tracking) than when is just asked to follow a target with eye [39]. This shows that there is a communication between sensory and arm motor system when is asked to follow a target with the hand and with the eyes [38]. Indeed, with the active movement of the hand, the smooth movement of the eye is more accurate [40]. When the subject needs to follow a target with the hand, the eye gives information about the target and its motion. The vision of the hand during its movement improves its spatial accuracy [41]. Moreover, it is possible to follow the hand moving under a table with the eye thanks to the proprioception but it is observed that movements of eyes are saccadic [42]. Finally, if visual attention is distracted during a reaching task, it is noticed that the performance of the movement is less accurate [43]. Indeed, the trajectory of a reaching movement can be modified if the target changes of position during the task with no vision of the hand [44]. The vision is mainly used to define the trajectory and kinematics of reaching movements. The proprioception seems to be crucial in converting the plan into motion commands sent to the arm muscles [24]. The efficient online motor control considers visual information about the target during point-to-point movements of reaching [23].

One more time, compare active movements with passive movements, it is observed that eye tracking is more precise during an active task where the target is the hand [45]. This can be explained by the fact that the oculomotor system uses afferent signals (muscle control signals) of the hand and arm to predict the movement [46].

2.4 Internal models

Internal models for motor control illustrate how organisms use input-output informations to perform oriented movements [47]. These models represent the interaction between the environment of the body, the sensory system and the motor system. It is a representation of the brain operation (Figure 6) with specific neural circuits [48]. The forward and inverse models are the two kinds of internal models analysed in this subsection [49] [6]. The inverse model provides input to human body parts in the form of motion commands to obtain the desired sensory output through the interaction of the human body and the environment [6]. While the forward model operates predictions of the sensory results of the generated motion commands. The body environment, the musculoskeletal mechanics and the central nervous system interact with each other to obtain the motor behaviour.

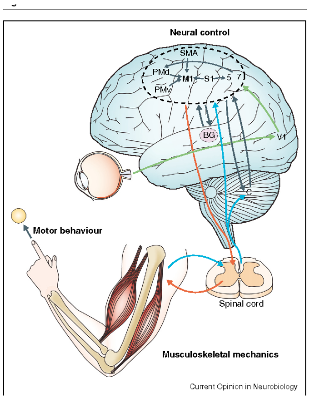

Figure 6: Interaction between musculoskeletal mechanics system, the environment and the central nervous system for motor behaviour results [50].

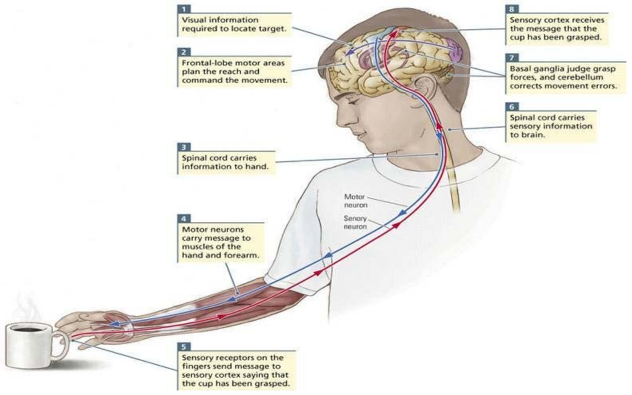

Figure 7: Grabbing a cup is an example of task where the internal model can be illustrated [51].

For a task like grabbing a cup (Figure 7), an internal model method of human sensory motor circuit is divided in three main step. In the first stage, the central nervous system considers physical environmental status and specific tasks to generate motion commands. The second stage observes the state change due to the motor command. The third stage provides sensory feedback about the new state. And these three phases are represented by separated internal models in the brain: inverse model, the forward dynamic model and the forward sensory model [6].

The purpose of the internal model is to solve a series of limitations faced by sensory-motor circuits in fast movements [5]. Indeed, this loop has some limitations as a delay in neuron transmission or in sensory feedback and can have sensory signals with noises and inaccuracies. These internal models adapt according to the environmental change and the body function.

The theoretical model proposed for the coordination between eye and hand is illustrate on the figure 8. Thus we can observe two systems, the first one for the eye motor (blue dotted line) and the second one for the hand motor. These two systems are similar and are resumed in a same model (Figure 9). On the figure 8, it is shown that there is coordination control centre between the system that uses as input the hand efference signals, the proprioceptive information and the visual input in order to improve the timing and the spatial accuracy. According to a study with deafferented subjects, it has been observed that there are indeed two distinct systems, one for the vision and the other for the proprioception in adaptive processes [52].

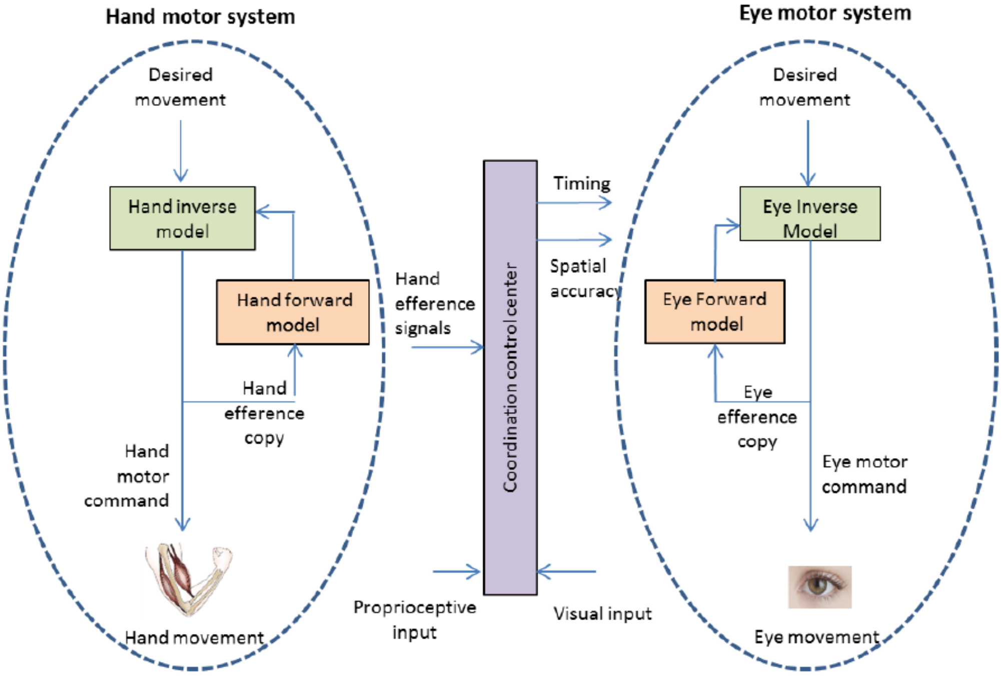

Figure 8: The theoretical model proposed for the coordination between eye and hand [6] [38].

In the following sub-sub-sections, the forward model and inverse will be described separately. In fact, it is two complementary systems where the inverse model allows the calculation of the motor control thanks to the state of the body and the desired movement and the forward model that uses the efferent copy and the motor command to obtain information on the sensory states.

2.4.1 Forward model

Thanks to the forward model, the motor commands are converted into sensory results with prediction. Moreover the longevity of the calibration exercise and an estimate of the state of the body and its surrounding world are generated by this model [47]. The sensory results are predicted by the model thanks to the motor commands. So the forward model receives a copy of the motor commands ("efferent copy") as input (Figure

9). The outgoing motion signal supports inferential discharge, and therefore can be used to predict the results of the action before the sensory feedback is available [5] [47]. Since the outgoing copy is coordinated with the motor signal and the output of the inference is coordinated with the sensory signals, the loop of the forward model is faster and less noisy which helps in rapid motions [6].

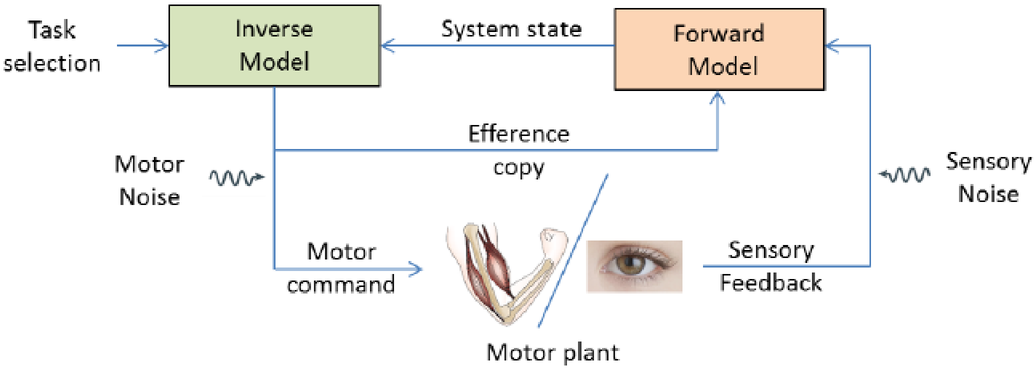

Figure 9: Role of forward and inverse models in motor behaviour [6].

Causal link is set by forward model between actions, sensory signals and dynamic results of system status and motor controls. An example of this model is for a tennis player who can accurately predict the trajectory of the ball that he wants to hit and coordinate the movement of the hand (racket) [10].

2.4.2 Inverse model

During exercise planning, the desired sensory results are converted into motor commands (Figure 9). This conversion is explained by an inverse model. This is the feedback controller. Sometimes it is also described as a control strategy, this feedback controller converts the state estimates of the body and the task target into the next moment's motion command [6]. Even if the exercise plan is started before the starting of the movement, the inverse model will continue to control the movement and correct errors during the execution of the exercise. After knowing the present position of the body according to the environment, the inverse model will tend to maximise the performance of the movement with adjustement in the sensorimotor feedback loops [6].

2.5 Aims of the thesis

As the title of this master thesis indicates, the main goal of this work is to study the "visuo-haptic coordination in tracking tasks". To achieve this, some data were collected on subjects with the KINARM robot at Woluwe. To understand this coordination, some conditions are used to separate different roles of vision or proprioception. Thus this work is composed of several principal goals.

The first aim is to study the **role of the vision in hand tracking tasks** (follow a target with the hand). So, a comparison of hand movements is done with and without visual feedback[1] of active hand motion[2]. In the same active movement of the hand, analysis of eye movements are realized. Moreover, we compare eye movements with and without visual feedback of passive hand motions[3].

An other principal goal of this work is to understand the **role of hand proprioception in eye tracking tasks** (follow a target with eyes). For this, we compare eye movements with and without active hand movement. In other words, in a first condition, we have active hand motion and eye motion while tracking a moving target with eyes and hand. In the second condition, we have hand rest and eye motion while tracking a moving target with eyes. We can also compare eye movements of this last condition with passive hand motion and eye motion while tracking a moving target with eyes.

Then, we contrast two different types of tracking trajectories: straightlines and curves where the straightline is more predictable than the second one. Finally, we compare if there is a difference between the use of the preferred hand or not during tracking tasks.

Regarding the analysis, between target and eye (gaze) or between target and hand, we mainly examine position errors, difference of velocities or lagging. For the eye movement, we want observe if there is a difference between saccadic and smooth pursuit mechanisms. For that, the mean amplitude, mean rate and percents of saccade distance are computed. Another issue is whether the direction of the trajectory has an influence on the different outputs. Finally, we want to know if the reaction time of hand or eye are different depending on the conditions of the experience.

As mentioned in the introduction section, understanding these systems of coordination more precisely could help in various fields as rehabilitation (stroke, accident...), operation, elaboration of new prosthesis devices, new robots like exoskeleton ...

3 Methods

To answer the different aims of this thesis, we need data. For this purpose, we explain the methods used with the material, the subjects and the protocol of experiment.

3.1 KINARM robot

Firstly, to collect data, we use the KINARM robot (Figures 10 and 11). The advantage of this robot is that we can create a variety of situations thanks to a programmable interface and more precisely tracking tasks for this protocol. As we can observe on figures, there are 2 handles that move in a horizontal plane. These handles are connected to robotic arms and allow to know some parameters as position, velocity and force accurately. During passive movements, the handle is moved by the robot and not by yourself. Then, the subject is seated on a height-adjustable stool in order to be as comfortable as possible. The head is placed against the robot to follow the animations on a black screen. This black screen is actually the projection of a screen on a mirror (Figure 12). With this

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[1] There is a visual feedback when it is possible to see the hand during a task.

[2] The hand is moved by yourself.

[3] Hand movement where the hand is not move by yourself. In this case, the hand is moved by the KINARM robot.

Figure 10: Scheme of KINARM robot [53].

Figure 11: Robot used at the institute of Neuroscience (COSY) in robotics and readaptation lab at Woluwe.

combination of a screen and mirror (at equidistance between the plan of handles and the screen), the subject can imagine where is the real position of the object in the handle's plan [5]. In this protocol, it is not possible to directly see the hand under the black mirror but we have a visual feedback of the hand thanks to a white dot that simulates the centre of the handle on the mirror.

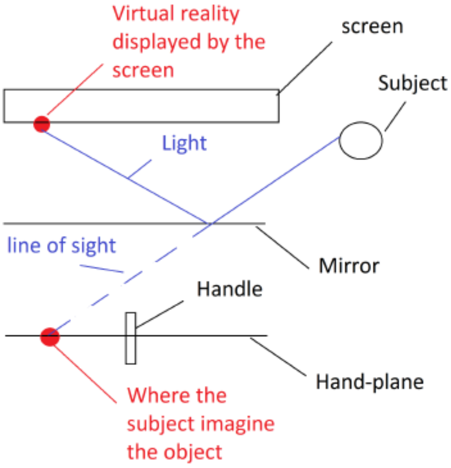
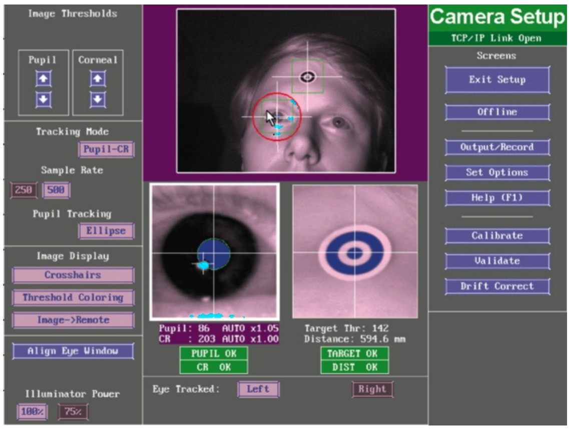


Figure 12: Black screen mirror to display virtual reality [5].

3.2 Eye Link 1000 Plus

To collect data of eyes, the robot used the **Eye Link 1000 Plus** of "SR research EyeLink ®[54]" as gaze tracker. This camera has an acquisition frequency of 2000 Hz. Thanks to a calibration, this gaze tracker has a very good precision and accuracy. This calibration is necessary before each session and consists to fix 13 centres of dot targets on the screen. A repetition of this 13 dots is realised as validation of the calibration. Moreover, it is possible to repeat the calibration if the parameters of accuracy are too poor. It is important that the subject does not move his head too much during the session of protocol (after the calibration).



Pupil: 86 AUTO x1.05
CR : 203 AUTO x1.00

Target Thr: 142
Distance: 594.6 mm

Figure 13: Eye Link setup [55].

There is a software (Figure 13) that can estimate the position of the gaze. So the subject needs to put his head against the robot, then he is asked to fix the camera to adjust the focus of this one on his dominant eye. Next, a target is put on head above the left lip (or on the forehead on this illustration) if the dominant eye is the right. This target helps to know the eye position and allows to not lose the signals during trials.

3.3 Participants

Twenty one volunteers came to the laboratory. However, three of them were rejected from the protocol after the first session (there are three sessions). Data of five others are not used for the analysis because signals are too noisy, lost and useless. Therefore, for the analysis that will follow, data from 13 subjects are used. We are witnessing the fact that data of these people being ejected based on the raw signals and not after analysis of contradictory representative values.

Age of participants are between 19 and 32 with mean age of 24.3 ± 3.1 years old. Of the 13 subjects analysed, 7 of them are girls. As desired, there are all right-handed. The preferential hand is verified with the test "*Edinburgh Handedness Inventory*" [56]. It is asked to sleep well the night before the experiment and not to be under the influence of drugs, alcohol or caffeine. If the participant have long hair, it is necessary to tie them back and makeup around the eyes (e.i. mascara) is forbidden. No one had any motor or neurological disabilities. All participants agreed to participate in this experiment and signed a consent form after having read it with them.

3.4 Experimental design

The protocol is composed of three sessions of approximately one hour each for a total of three hours of acquisitions. One session for active movements, an another one for passive movements and the last one with the left hand (not preferential hand). The sessions can take place over two or three different days. If the last two sessions took place on the same days, a rest of half an hour is done to the subjects between them. There are two kinds of trajectories during tracking tasks, the curve trajectory and the straight line trajectory. Each sessions are composed of several conditions and blocks. The order of the sessions is random as well as the order of the blocks in these sessions. These sessions are detailed one by one in this subsection after explanations about different trajectories and eye calibration.

3.4.1 Trajectories

There are two kinds of trajectories for the target (Curve and straight line) in this experiment of tracking tasks. Here, the characteristics of these two types of trajectories will be discussed in more details.

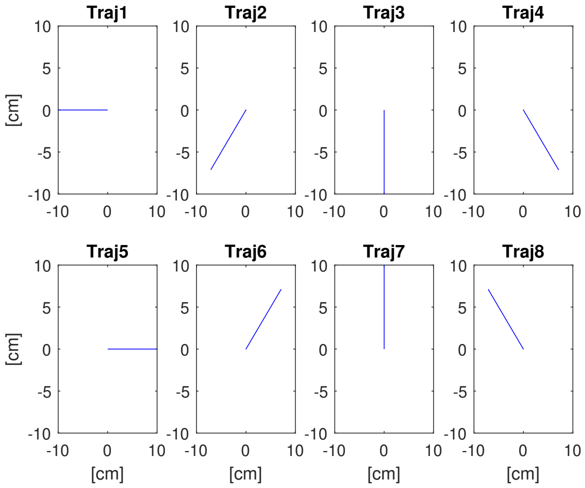


Figure 14: Eight straight line trajectories.

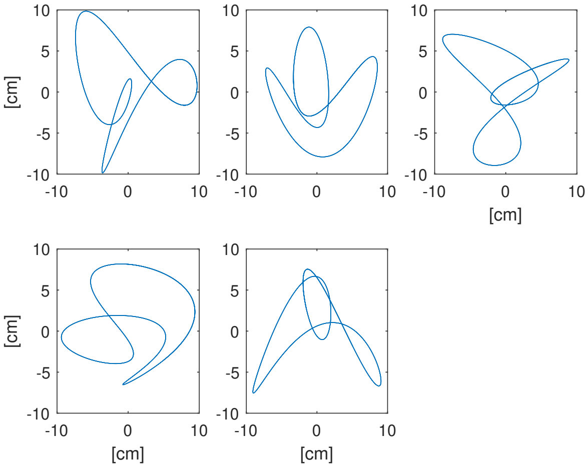


Figure 15: Five curve trajectories [57].

Firstly, in the figure 15, the five cycle curve trajectories used are illustrated. We can observe that each path of targets are in a twenty centimetres centered square. The target needs 5 seconds to realise these cycles. For a trial, the cycle repeats itself to have 10 seconds of movement. These paths are unpredictable and participants do not see that the cycle is repeated during a trial. The five shapes used come from another study of F.R. Danion and J.R. Flanagan [57]. The five paths are constructed with a combination of two cosines for the positions along x-axis (Equation (1)) and a combination of two sines on y-axis (Equation (2)).

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

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

The parameters [57] used for the five curve paths (Figure 15) are in the table (1) where φ represents the phase and h the harmonic. To have a cycle of five seconds, the values of the parameter ω is set at $\frac{2\pi}{5}$.

Trajectory	A_{1x} [cm]	A_{2x} [cm]	h_x	φ_x (°)	A_{1y} [cm]	A_{2y} [cm]	h_y	φ_x (°)
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 1: Parameters of equations (1) and (2) for the five different curve trajectories of target [57].

Then, we can observe on the figure 16 for one cycle of the first curve trajectories the x-axis and y-axis positions with the combination of two trigonometric functions on upper blue plot. In red, the derivative of these positions give the velocities along the axis. The target moving in a horizontal plane, we are interested by Cartesian velocity $V_{XY} = \sqrt{V_X^2 + V_Y^2}$ which is illustrated in the lower left plot of the figure 16. It is interesting to note that the mean velocity of the five trajectories is the same and has a value of 16 cm/s. Moreover, the X-Y velocity is never nil and the target starts to move with a speed of approximately 11 cm/s in this first trajectory. This velocity has a maximum of 27 cm/s.

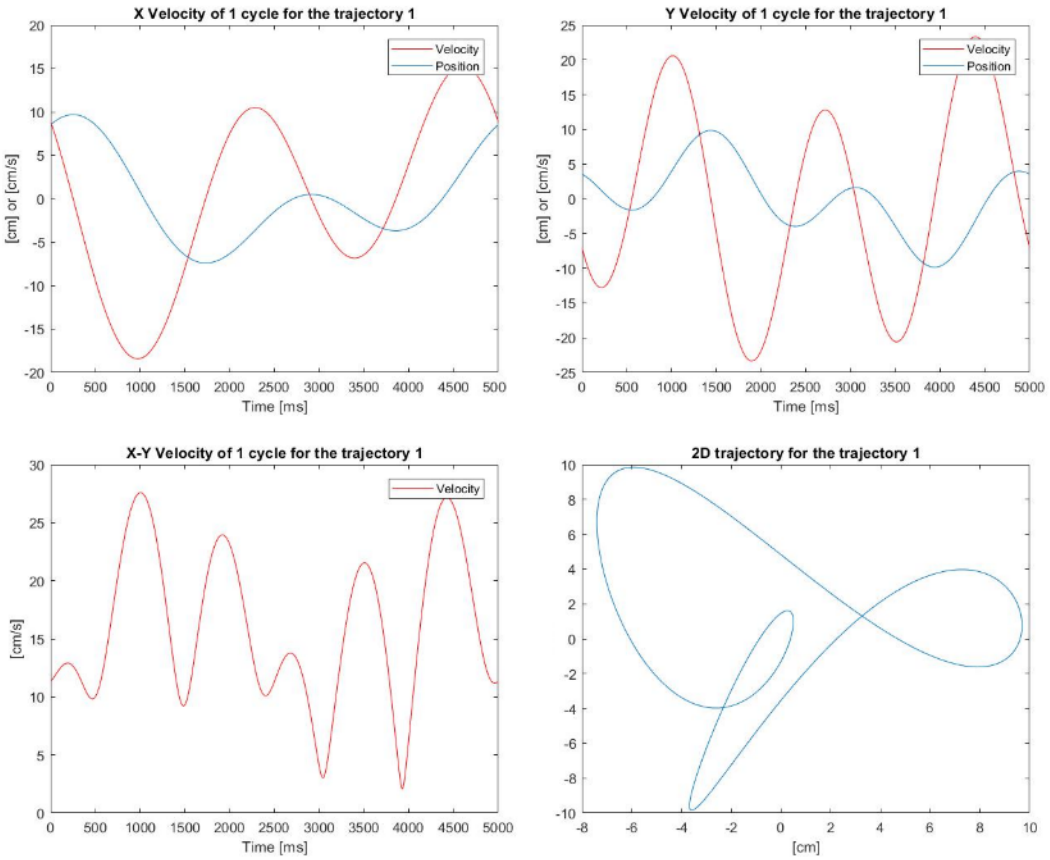


Figure 16: In upper plots for one cycle of the first curve shapes, the positions in x-axis and y-axis are in blue and the velocity along axis in red. In lower left is the Cartesian velocity and in lower right is a remember of the first path.

Concerning the straight line trajectories (Figure 14), there are eight directions with a length of ten centimetres which we go through in two seconds. The starting point is always the same and the straight trajectory is very easy and predictable. As long as the target has not started moving, the subject does not known the direction to follow. However, after the target's departure, we can predict the way to be follow and the arrival point.

As for the curves, in figure 17, we can observe the information about velocities. In this case, it is for a starting point at the centre of the screen and an upward trajectory to the left. The shape of the X-Y velocity is the same for all directions and begins with a nil velocity and rises to a peak of 10 cm/s at midway. Then the speed decreases to zero.

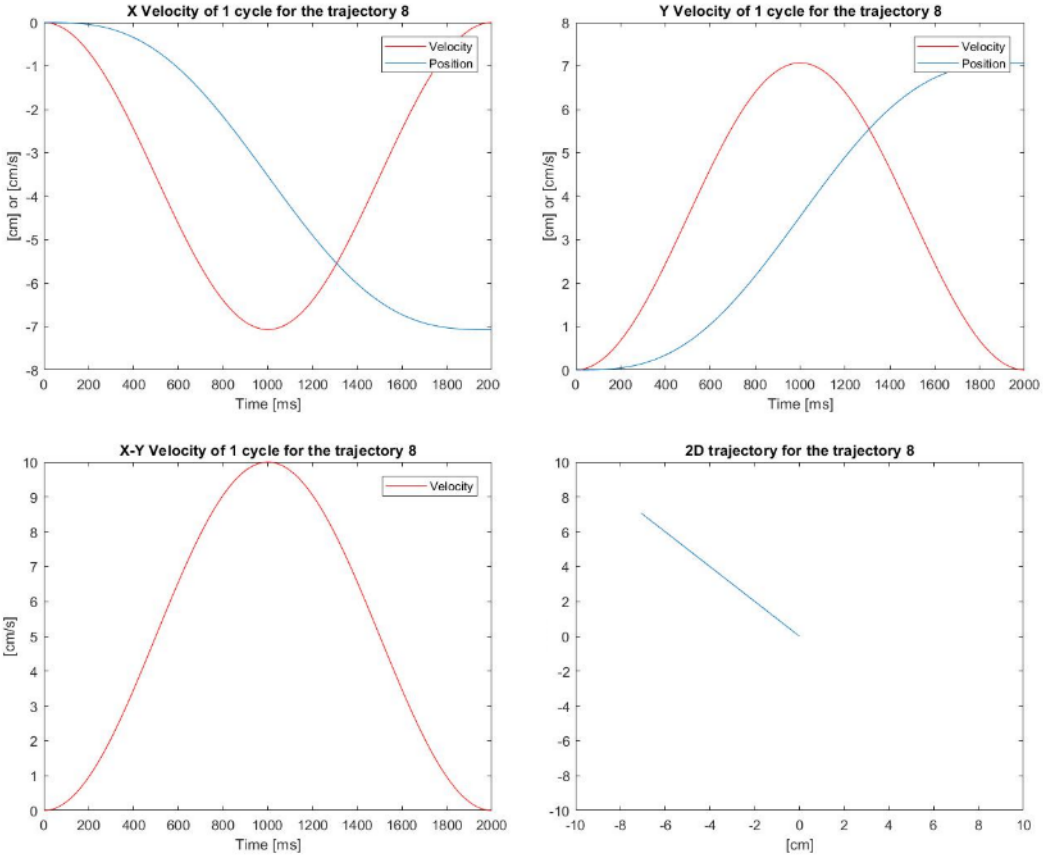


Figure 17: In upper plots for the eighth straight line shapes, the positions in x-axis and y-axis are in blue and the velocity along axis in red. In lower left is the Cartesian velocity and in lower right is a remember of the eighth path.

3.4.2 Eye calibration

Before to start tracking tasks of the session, it is necessary to calibrate the set up of gaze tracking on the dominant eye[4] of the subject. This step can be done very quickly for some subjects if the calibrations obtain good parameters from the first test but sometimes it takes several tries. This calibration consists in fixing twice 13 white points on the black mirror. First time for the calibration and the second time for the validation of parameters. Once this calibration is done, the participant is asked not to move his or her neck and head too much during the session. This is a little uncomfortable and that is why we are asking people to be well seated. It is also necessary to make sure that

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[4] A short exercise is done with the participant to know this dominant eye.

the target on the face (Figure 13) is well stuck because it allows to locate the eye in space.

Then another small calibration (only one try) with eleven points is done before each blocks of the session. This one, to make sure that the calibration is still good. Otherwise an adjustment is applied at following data (more details in the subsection 5.3: Eye signals correction).

3.4.3 Different conditions

To remember, the protocol is divided in three sessions for 14 conditions. For a participant, these sessions are randomised as well as the order of the blocks in these sessions. Ten conditions (A-J) are represented in the figure 18, the four others are the same as the conditions A,B,E and F but we use the left hand (AL,BL,EL and FL).

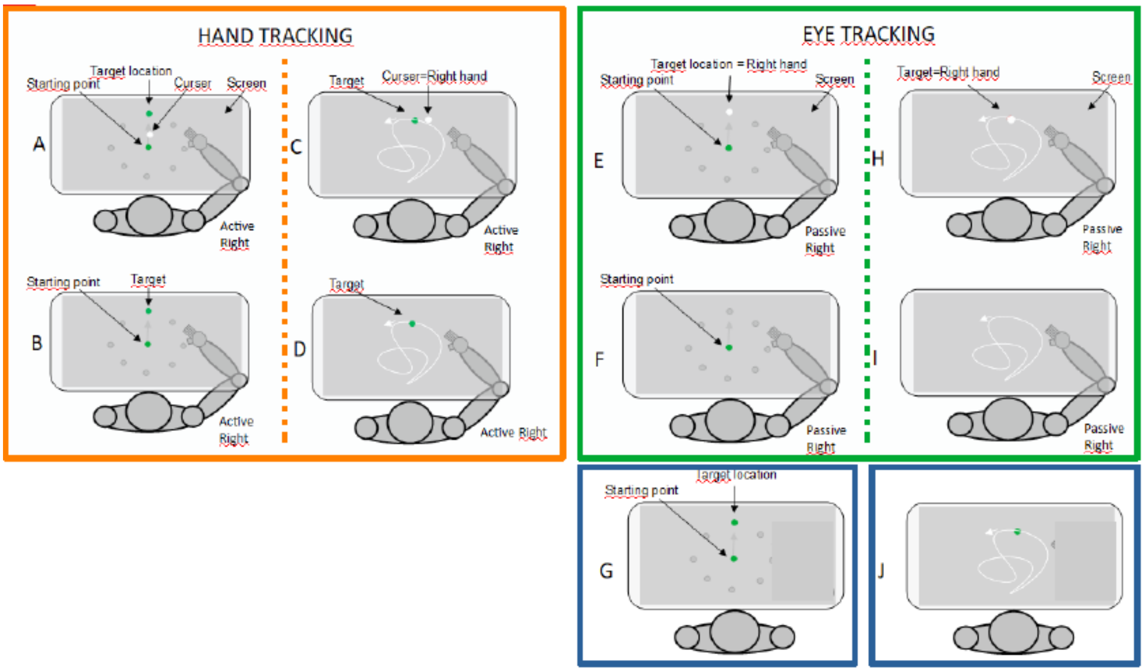

Figure 18: Ten conditons (A-J) for the active session and passive session. Hand tracking in orange, eye tracking with the hand in green and only eye tracking in blue.

Active session

This first session is composed of three blocks. Two blocks of hand tracking (Figure 18: orange) to study the role of visual feedback in hand tracking and a third block (condition G in blue on the figure 18) to study the role of hand proprioception in eye tracking task. We name this session *active session* because during hand tracking (orange), the subject moves the handle by himself. The condition G is not an active movement of the hand but it is put here to complete the session of one hour.

We can start by explaining the second block of hand tracking with conditions C and D before the first block of conditions A and B. Then we describe the conditions of the block separately.

For the **condition C**, it is asked to follow a green target with the hand and with the eye. There are ten trials of ten seconds for this condition with curve trajectories. On the black screen the participant sees the green point of the target and a white point (visual feedback) that represents the centre of the handle (the hand). A trial is ready to begin when the start point (green point) appears on the black mirror. Then, to start the trial, the participant needs to put the white point of the handle on this starting point, the target begins to move after a small delay. We collect data during the movement of the target. Concerning the gaze, the goal is to be focus on the target (green point) and not on visual feedback (white point) even if this one will be in general not far away. For the hand the goal is to "follow" the target and for that the visual feedback indicates precisely where the hand is located. By "follow", we want to be on top of the target during the trajectory but since this is unpredictable, the participant tries to stay as close as possible to that target during its movement. The trial stops when the target has finished its movement and disappears.

The goal of the **condition D** is exactly the same, it is necessary to follow the target with the eye and with the right hand. The only difference is that the participant has not visual feedback during the trial (the white dot is not visible). The trial begins in the same way when the target starts to move after putting the visual feedback in the starting point. But the visual feedback disappears when the target starts its movement. This hand tracking task may seems harder because the subject has not visual feedback to know the exact position of his hand, he can just use proprio-sensors to imagine the position of his hand.

This block is composed of twenty trials (10 of C and 10 of D) that appear in a random order. Thus the subject does not know before starting the trial whether he will get a visual feedback or not during this one. Moreover, the subject can take his time to play the following trial because he launches the next trial by himself when he puts his hand in the starting dot. Thus it is asked to blink before the next trial as it is better to avoid blinking during the ten seconds of run. A break is given after ten trials so that the person can rest their eyes with small exercises learned before the experience begins. During this break, the participant can also release the handle but not move the neck or the head to avoid losing the eye calibration.

The first block with condition A and B is similar to the second block (C and D) with active movement of the hand but this time with straight line movements.

The **condition A** is composed of eighty trials of active movements of 2 seconds with visual feedback of the hand. Thus, each of the eight directions is tested 10 times. The instructions are exactly the same as for the condition C.

Concerning the **condition B**, it is the same as condition D but with straight line paths and eighty trials.

Consequently, the first block is composed of 160 trials (80 of A and 80 of B). Even if one trial takes only 2 seconds, this block lasts approximately twenty minutes. For that reason three breaks are given during the block to rest eyes and hand. The order of trials is random so the participant does not know the direction or the presence of visual feedback for the following trial. However, the path and the final point of the target are easy to predict so it is very important to remind to the participants that it is a tracking tasks and not a reaching tasks. The goal is to *follow* the target and no directly go at the final point.

Finally, only the **condition G** constitutes the third block. This condition involves only eye tracking with the rest of the hand. There are eighty trials with straight line paths and a random order. The trials follow each other but there is a small lapse of time between them to allow subjects to blink. This last block requires three breaks to rest the eyes.

Passive session

This second session is also composed of three blocks. Two blocks of eye tracking (Figure 18: green) with passive movement of the hand and a third block with the hand at rest (condition J in blue on the figure 18) to study the role of hand proprioception in eye tracking tasks. We name this session *passive session* because there are two blocks with passive movements where the handle is moved by the robot. The block with condition J is put in the session to balance the duration of the sessions of approximately one hour.

As for the active session, we start by explaining the block composed of curved trajectories (conditions H and I). Then, we quickly explain the passive movement with straight line paths (condition E and F) and end up with condition J.

For the **condition H**, the goal is to follow the right hand with the eye during passive movements of the handle. To help, the visual feedback of the hand is plot on the screen. Henceforth, the target and the hand are confused in this condition. Then it is asked to follow the white dot with the eye. As for the active condition, a trial is ready to begin when the starting point (green dot) appears on the screen. Then, to start the trial, the subject needs to bring actively the visual feedback of the handle in this starting point. After a very short time, the handle starts to move by itself (passive movement) and the collection of data begins. There are ten trials with a duration of ten seconds. When the handle stops moving by itself, the collection of data is finished for the trial.

The goal of the **condition I** is exactly the same that the previous condition H, that means following the centre of the hand with eyes. However, there is no visual feedback of the hand so it is asked to follow the hand as there is the white dot but on a black screen (nothing is plotted on the mirror). The participants have to guess the position of the hand thanks to proprio-sensors. Concerning the beginning and the end of the trial, it is similar at the condition H but the visual feedback (white dot) disappears when the KINARM robot takes the control of the handle.

The block is composed of twenty trials including ten for condition H and ten for condition I. The order of trials is random so that the participant does not know before the trial if he will get a visual feedback (white dot) during this one. As for active session, the subject can take its time to play the following trial to blink before starting. A break is necessary after the tenth trial. We warn that the handle starts quickly and stops abruptly but the arm must not resist to the robot.

The **condition E** and **condition F** correspond respectively to condition H and condition I but with straight line movements of the handle. Thus this block is composed of 160 trials (80 for E and 80 for F) of passive movements with straight line paths. Every trials have a duration of 2 secondes. The order of trial is random, thus the participant does not know the direction path or if the white dot will be plotted before the starting of trial. It is a tracking tasks and not a reaching one so it is remembered that the goal is to follow the centre of the hand during the movement.

The third block contain only the **condition J** where the goal is to follow with only eyes ten curve trajectories of ten seconds. Three breaks are given to rest eyes because it is tiring for the eyes to not blink for several successive trials.

Left session

For this left session only straight line movements are studied and the participant uses the non-preferential hand (left hand) on the right handle. The goal is to observe if there is a difference in results according to the hand used. Thus we repeat the first block of the active session of conditions A and B but this time we call these conditions **AL** and **BL**. Then, the second block with condition **EL** and **FL** corresponds to the first block (conditions E and F) of the passive session.

4 Programming Environment

The figure 19 illustrates the communication between the KINARM robot and the computer. Indeed, some data are collected by the eye tracker and by the handle of the robot. Then the computer submit some orders to the screen (visual feedback, target) and the handles (motors for the passive movement). Several kinds of sensors are in the handles but only positions of them in time are collected for this protocol.

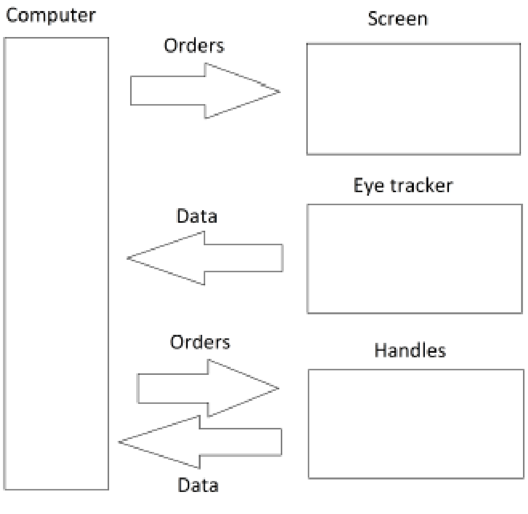

Figure 19: Link between the computer and the KINARM [5].

Then, the software that controls the KINARM robot is the Dexterit-E which used the files .dlm and .dtp generated by the simulink program of Matlab [5]. The robot needs the .dlm file that contains the general protocol with the different trajectories and conditions of blocks and trials. This file is exactly the same for each subjects. Conversely, the .dtp file is more adaptable and changes according to the order of the blocks or according to some parameters that is possible to change. Finally, the data are saved in a .zip file.

5 Data processing

Once the data are collected with the robot, we can analyse them with Matlab. Before that, it is necessary to extract the different signals that we need of the .zip file. Thanks to the KINARM robot, we know the position of the handle and the target over the time. The gaze position is collected by the eye tracker. These signals are sampled at 1,000 kz. Thus, signals of one trial have 2,000 samples for a straight line trajectory and 10,000 samples for a curve trajectory. It is also necessary to detect when the trials begins with the "*EVENTS.LABELS*" send by the KINARM. Then, all trials are classified by conditions. A number is associated with each trial according to its direction for straight line paths (8 different numbers) or according to its curve trajectories (5 numbers). The signals for the position of the handle and the target can be used in this raw state but that is not the case for gaze signals. The eye signals need more work, it is necessary to extract noises, to remove blinks (or outlying parts), to detect saccades and to correct position errors. In this section, we explain these different steps to obtain data usable for gaze position.

5.1 Blink removal

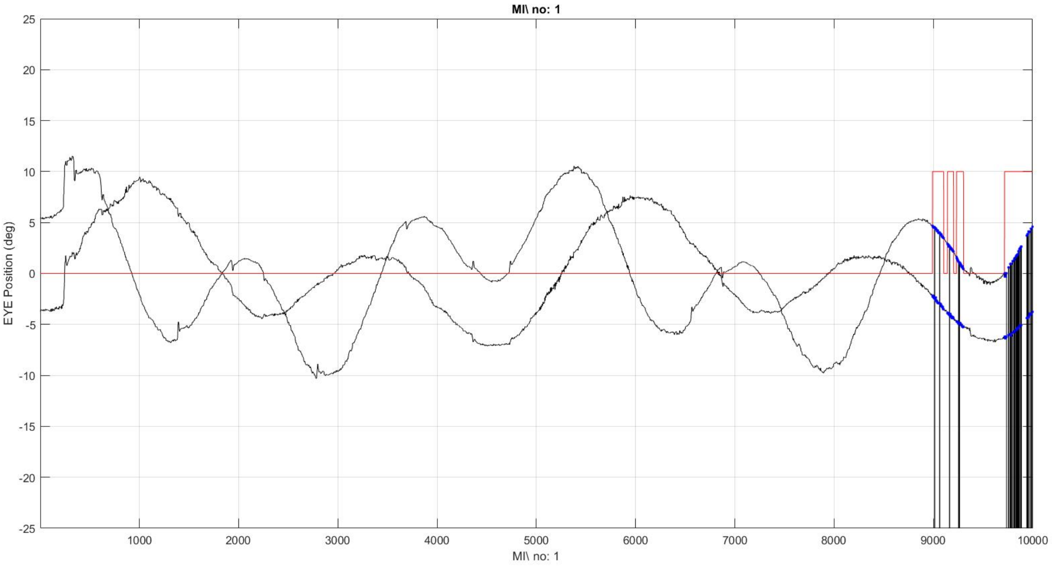

Figure 20: Window displayed by function "MarkKinEyeBlink" to remove blinks. Plot of X position and Y position of gaze for a trial with curve trajectory. When the value of the red line is different of zero, it is a automatic detection of blinks.

When the participant blinks, the gaze tracker can no longer detect the eye and loses a part of the signal. This loss of the gaze is represented by absurd values (big outliers for x and y positions). Thanks to these absurd values, the Matlab code "blinkremover2.mat" detect and remove these blinks automatically (see red line different of zero in figure 20). However, this Matlab function does not detect all the blinks and bad data. Several issues can make that some parts of the signal need to be removed. It is the case when hair or an eyelash falls in front of the eye[5]. Some parts of the signal are very noisy. Lastly another reason comes from the eye tracker that has some difficulties to track the pupil while the eye is wide open.

Thus, we can remove these wrong data manually thanks to an adaptation of the code "*MarkKinEyeBlink.mat*" of Dc. Jame Mathew. By "remove", we mean that this parts of signal are ignored during the analysis. An alternative solution proposed by this function is to interpolate the deleted part but that would imply errors in analysis. Firstly, because the interpolation suggested is linear which is not ideal for large signal losses (Figure 21). Then, it is not necessary to have full signal for the different analysis.

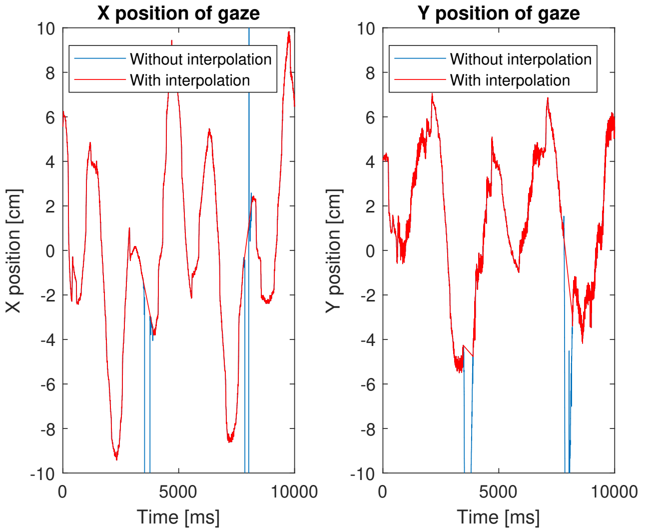

Figure 21: Solution? Linear interpolation of blinks for one curve trajectory trial.

The manual removing, is done with simple clicks on the window of the figure 20. This step takes a long time because there are 770 trials by subject and thus 770 windows to observe with some clicks. For that reason, it is necessary to be well concentrated in order to avoid having to do it all over again and directly get correct data.

5.2 Saccades detection

Several analysis will focus on the saccades in this thesis thus it is necessary to detect them. In addition, we analyse the speed of movement of the gaze in relation to the target. Besides the blinks, it is also required to remove saccades for the analysis of velocity

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[5] Normally the participant's hair is tied back.

because it seen that there were some spikes of velocity during saccades.

As for blinks, it is possible to detect automatically some saccades (in deep blue on the figure 22). This can be done thanks to two thresholds. As seen in section 2.1.1, during a saccade, there is a peak of velocity accompanied by a very high acceleration. Consequently, a threshold of 30°/s for velocity and of $1500°/s^2$ for acceleration are used. These thresholds are too binding so all saccades are not automatically detected. One solution would be to have smaller thresholds as 20°/s for velocity and $1200°/s^2$ for acceleration but in this way the function gives false saccades. The solution is therefore to detect the missing saccades manually.

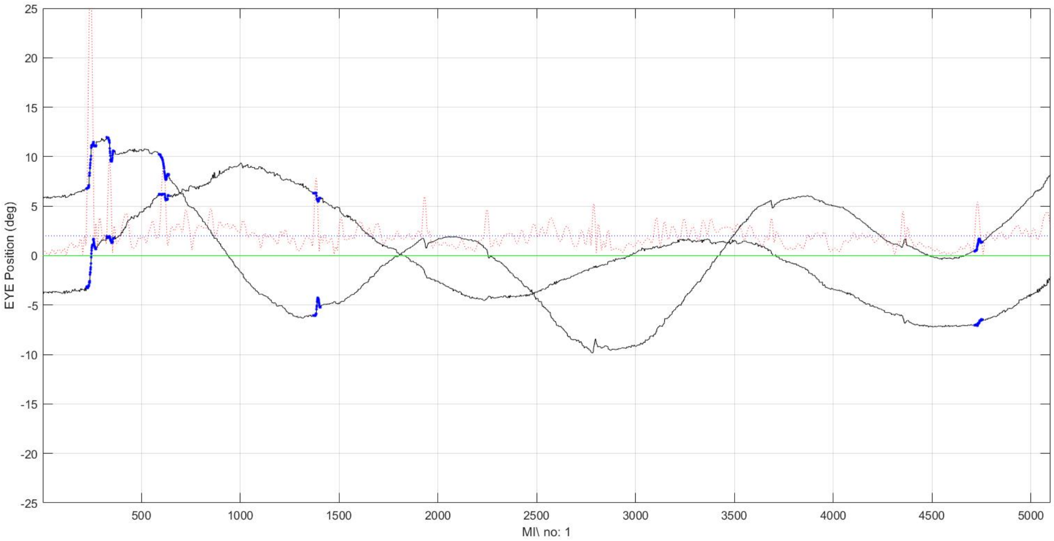

Figure 22: Window display by function "MarkKinEyeSacc" to detect saccades. In black, x-position and y-position of the gaze. Green line illustrates the presence or not of blinks. In light pink, Cartesian velocity of eye. In deep blue, automatically detected saccades.

The adaptation of Matlab code "*MarkKinEyeSacc*" allows to define these saccades manually. To help, in addition of the x-position and y-position of the gaze, the Cartesian velocity is plotted on the windows (Figure 22). The number of additional saccades is indicated to the program, then the beginning and the end of each saccades are determined by clicks on the windows. Two windows are used for one trial for a better view. Thus for this step, we observe 1540 windows $(2 * 770)$ for each participant. This consumes a lot of time so it is necessary to be focused during this repetitive and tedious task.

5.3 Eye signals correction

As explain in the section 3.4.2, there are a main calibration of the eye tracker before the session and another smaller calibration before each blocks of the session. These small calibrations are inspired by the Matlab code "*ProcessEyeCalib.mat*" [5] and indicate the induce constant error generated by the eye tracker. During these calibrations, it is asked to fix eleven dots (Figure 23).

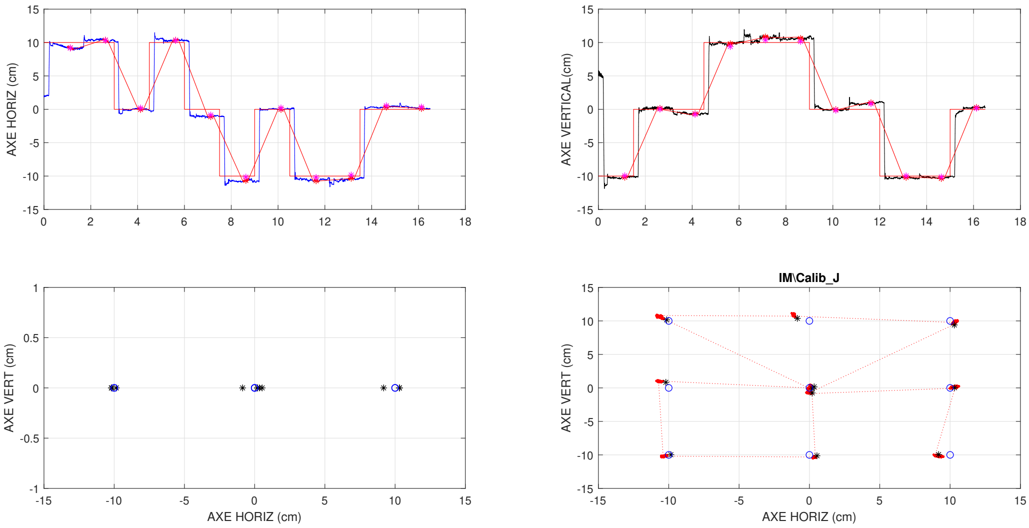

Figure 23: Figure display by function "ProcessEyeCalib.mat" to indicate eye correction for the corresponding block.

The error may be due to the first calibration that is not excellent or little moves of the head. Indeed, the eye tracker estimate the gaze position thanks to the position of the pupil in relation to the position of the face's marker (target over the lip). It is not possible for the participant to remain still during blocks so this calibration just allows to minimise the error.

Thus, a gain and an offset is computed with the Matlab function for each axis and are applied to eye signals of the corresponding block to obtain new eye signals (Equation 3 and 4) with a minimised error [5].

$$EyeSignal_{X,new} = EyeSignal_X \cdot Gain_X + OffSet_X \tag{3}$$

$$EyeSignal_{XYnew} = EyeSignal_Y \cdot Gain_Y + OffSet_Y \tag{4}$$

5.4 Low pass filter

Lastly, the sampling of eye signals obtained by the eye tracker are noisy. Thanks to a low pass filter, the signals are smoothed (Figure 24). The low pass filter used is the "*butter*" function of Matlab with a cutoff of 25 Hz. Thus the filtered signal can be derived to obtain velocity of the eye movement.

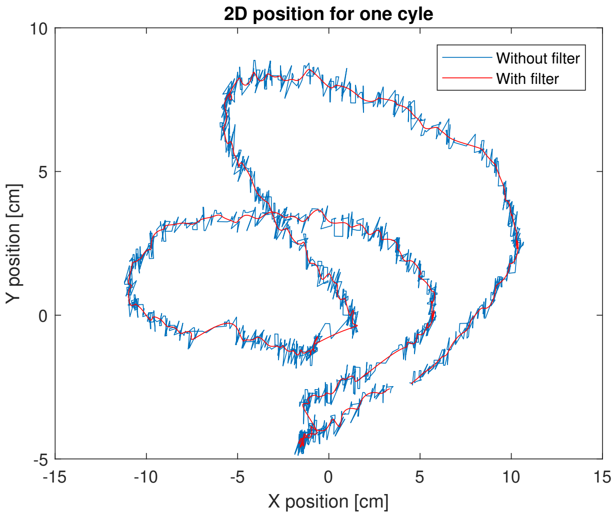

Figure 24: Display of the 2D position of eye before (in blue) and after the application of the low pass filter (in red).

6 Results

Since there are several aims in this thesis, the results will attempt to address these through several sub-sections. Indeed, the role of vision in hand tracking will first be studied. Then the role of proprioception in eye tracking follow-up by the role of hand used. For these analysis, the typical trials will be first illustrated to give an idea of the different movements (target, hand and eye). Afterwards, some parameters are calculated and are plotted in graphs. Finally, it is necessary to check whether the visual observations on graphs are statistical significant.

The results contain also sub-sections about the saccadic pursuit, the reaction time, the role of the hand used, the influence of path predictability, the role of the direction...

6.1 Vision for action: role of vision in hand tracking

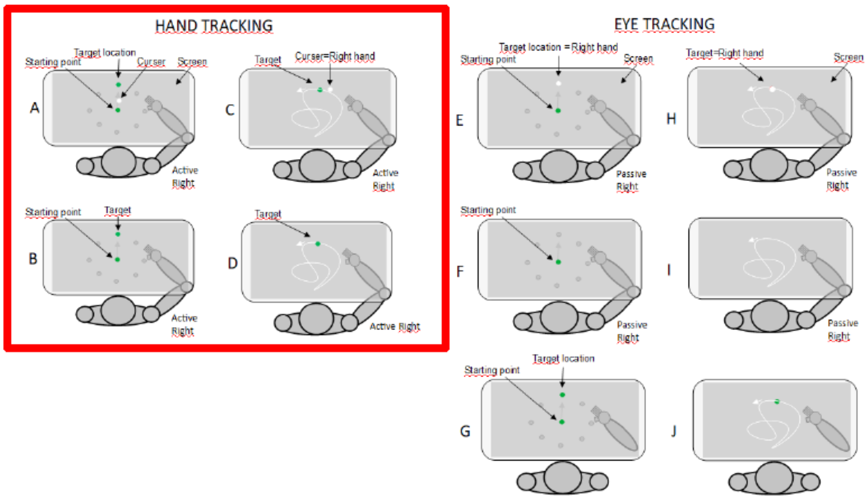

Figure 25: Red frame: four conditions used to study the role of vision in hand tracking.

To study the role of vision in hand tracking, the active movements are analysed (Figure 25). Thus, four conditions are used: two conditions with straight line movements (A and B) and two others with curve paths (C and D). To remind, the goal of these tasks is to follow the target with the hand and the eyes (with or without visual feedback).

6.1.1 Typical trials

It is interesting to represent typical trials before analysing with numbers.

In this way, the figure 26 shows a typical trial for **condition C** where the subject follows a green target with the eyes and the hand. To help, the visual feedback (white dot) is plotted on the black screen. The two upper graphs represent respectively the x positions and y positions in the time (10 s). The two others display the 2D positions separated by cycles.

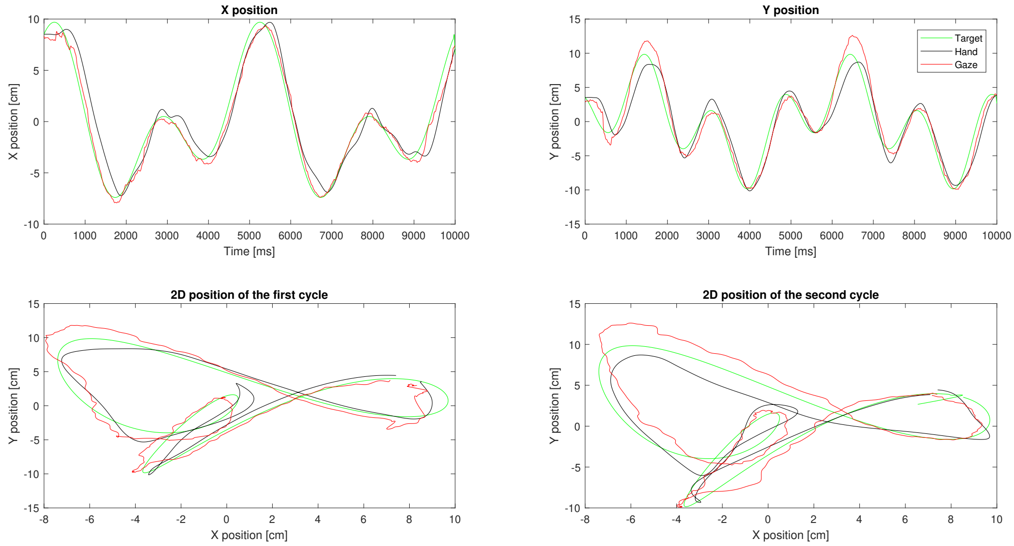

Figure 26: A typical trial of condition C

In that respect, we can observe in green the position of target that is complied with the curve path presented in section 3.4.1: cosinusoidal for x-position and sinusoidal for y-position.

The black line has a smooth appearance and is very similar to the target's trajectory but with a spatial inaccuracy (2D position on figure 26) . Another imprecision is observed concerning the time delay that is visible on the two upper graphs of the figure 26. Indeed, the black line is shifted to the right compared to the green line.

The red line reflects the gaze position. Directly in spite of the low pass filter, we observe that this line is less smooth. However the shape of the gaze's trajectory is similar to the target's path.

The figure 27 shows a typical trial for the **condition D**. The colour legend is the same that the previous figure for condition C. The statements are also similar to the condition C with the exception of the hand inaccuracy that is greater when the visual feedback is absent.

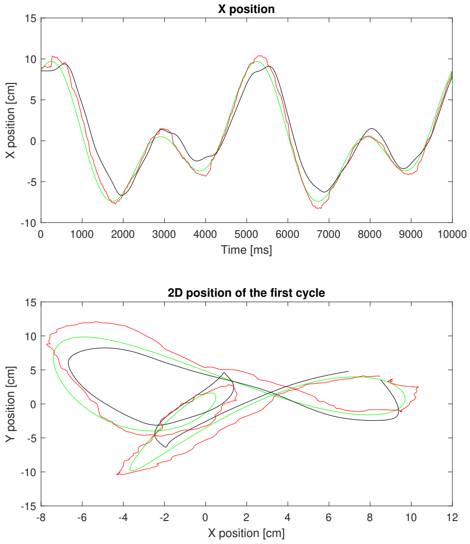

Figure 27: A typical trial of condition D

Finally, the typical trials for **condition A** and for the **conditon B** are respectably shown in figures 28 and 29. It is for a trial starting in the centre of the screen (0,0) and ending in the bottom right corner. It can be seen that the hand fit well the target's trajectory.

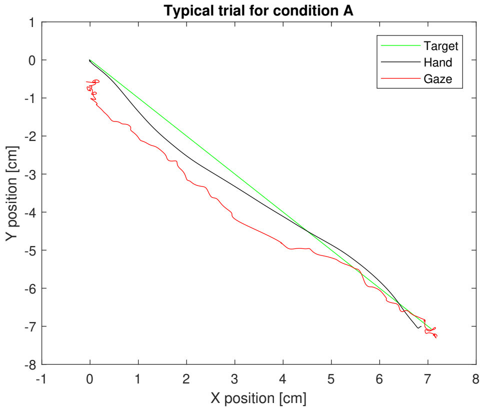

Figure 28: A typical trial of condition A.

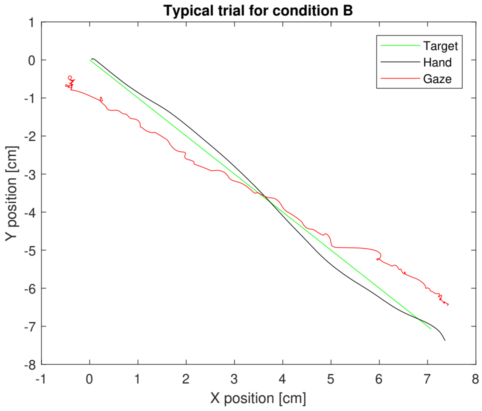

Figure 29: A typical trial of condition B.

6.1.2 Is visual feedback necessary for spatial accuracy?

The first question is to know if the visual feedback increases the precision of hand movement in relation to the target. To answer this question, the position error (PE) is used. For one trial, the position error between the target and the hand is the mean of the distance between them in time. This way, the figure 31 shows the mean position error per conditions for each participants (one colour by subject). The thick blue lines are the mean of all subjects and are representative of the general observation needed. The exactly same analysis (position error) can be done between the eye and the target (Figure 30).

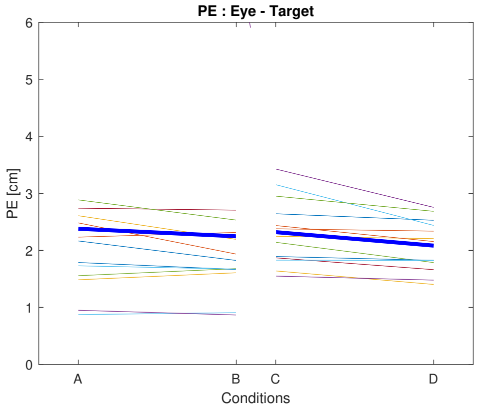

Figure 30: Mean position error between eyes and target by condition. One colour by participant. The thick blue lines are the mean value of all subjects.

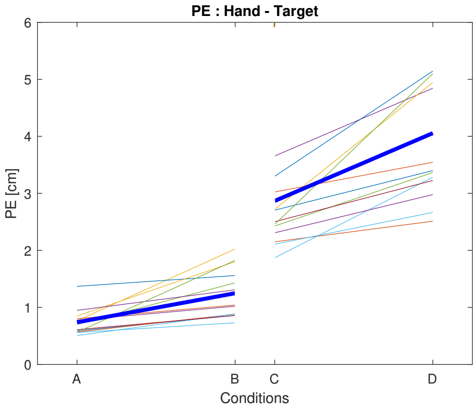

Figure 31: Mean position error between hand and target by condition. One colour by participant. The thick blue lines are the mean value of all subjects.

Concerning the position error between eye and target (Figure 30), the presence of the visual feedback or not does not statistically impacted it. Indeed, the thick blue line between condition A and B seems horizontal (p-val : 0.8373). Even though the blue line seems decreasing between condition C and D, the difference is not statistically significant with a p-value of 0.262 (>0.05). However, an explanation can be given about this decreasing [2]. When, subject is asked to be focused on the target (green dot) but the visual feedback is plotted, the gaze is attracted to this last. Thus, the gaze is on a line between the target and the visual feedback (Figure 32). This way the position error is slightly larger when the visual feedback is plotted because the gaze is disturbed by this one. Conversely, the vision is not impaired when there is only the target on the screen. This decreasing is not noticeable with straight line movements because as explained in the next paragraph, the path is more predictable so the visual feedback is closer to the target.

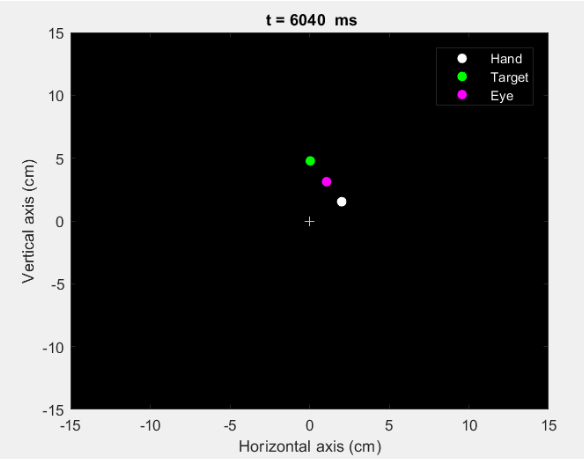

Figure 32: Position of the gaze (pink dot) when the visual feedback (white dot) is plotted. The green dot is the target.

For the position error between hand and target (Figure 31), an increase of the error is observed in both kinds of trajectory movement when there is no visual feedback. Indeed, these differences are statistically significant with a p-value of 0.0011 (p-val < 0.05) for straight line movements (conditions A and B) and a p-value of 0.0256 for curve trajectories (conditions C and D). Directly, we can see that the visual feedback is necessary for a better spatial accuracy. Another observation is the difference between straight lines and curve trajectories, the position error is much greater when the paths are not predictable.

6.1.3 Does the visual feedback have an influence on the tracking speed?

The mean velocity error is computed as the position error in every time step. Only the smooth pursuit is used for the velocity error between eye and target. Indeed, the blinks are ignored in data and saccades are ruled out because the peak of velocity would distort results.

Concerning the smooth pursuit velocity error (Figure 33), the presence or not of the visual feedback seems not to have effect on this one (p-val $= 0.9893$ for A and B, p-val $= 0.4621$ for C and D). One more time, this can be explained by the fact that the goal of the task is to follow the green target and not the feedback (white dot) with the eyes. This time, the type of trajectories is important because it is observed that velocity error increases when the path becomes less predictable.

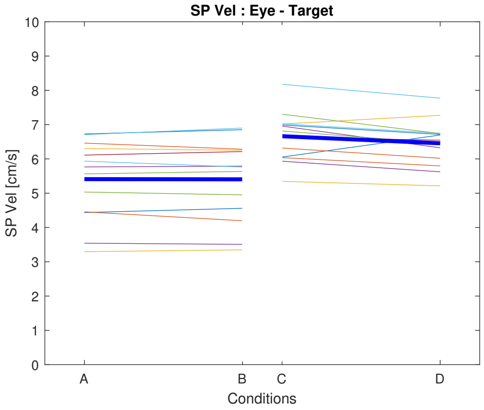

Figure 33: Mean smooth pursuit velocity error between eye and target. The thick blue lines are the mean value of all subjects.

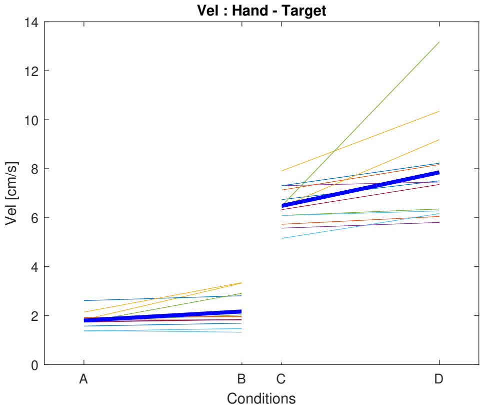

Figure 34: Mean velocity error between hand and target. One colour line by subject. The thick blue lines are the mean value of all subjects.

The velocity error can also be analysed between hand and target (Figure 34). Directly, it is observed that the error increases when the trajectories are not predictable. Then, if we are focused on the two conditions with curve trajectories (C and D), the velocity error increases when the visual feedback is absent. The participants have a tendency to make smaller or bigger movements when the visual feedback is not plotted so this growth is correlated with the position error. This increase is statistically significant with p-value of 0.036. However, it is not the case for conditions with straight line movements (A and B) where no statistical difference is observed (p-val $= 0.0951$). Although for some subjects an increase is noticeable but it is not a generality.

6.1.4 Is visual feedback necessary for temporal accuracy?

The question is to know if the visual feedback has an influence on the temporal precision. For this purpose, a correlation is calculated between 2D signals by gradually shifting the two signals by 1 sample. This correlation is computed with the function "*crosscorr2D.m*" of Matlab. The lag value corresponds to the shifting with the highest correlation. A positive lagging corresponds to delay of the eye or the hand in relation to the target. Here, the results are little more varied in hand tracking tasks but it is possible to draw some conclusions about lagging.

Concerning the lag between the target and eye (Figure 35), a statistical significant (p-val = 0.0025) decrease is observed when there is no visual feedback with curve trajectories. This can be explain with the same observation of the position error where the gaze is between the target and the visual feedback (Figure 32). For the conditions with straight line movements (condition A and B), the averages are more confused from one subject to another as well as the decrease observed on the figure 35 is not statisticaly significant with p-value of 0.1201. The lag seems to be smaller when the trajectories are predictable.

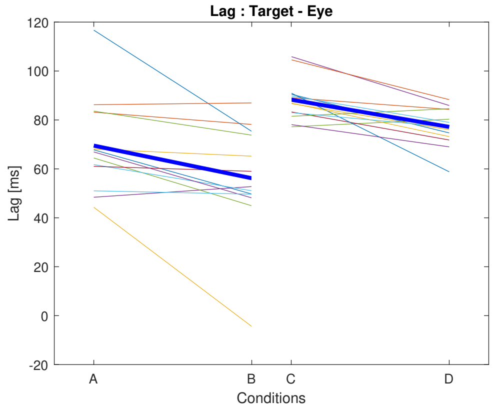

Figure 35: Mean lag between target and eye. The thick blue lines are the mean value of all subjects.

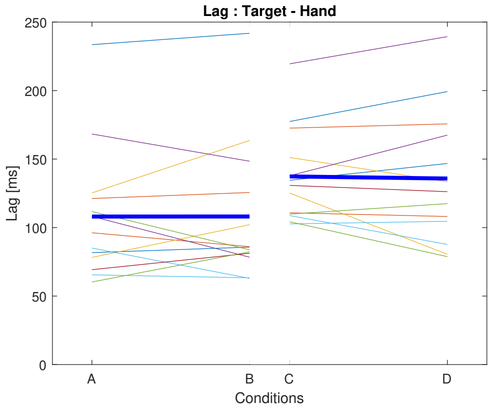

Figure 36: Mean lag between target and hand. The thick blue lines are the mean value of all subjects.

The lag between target and hand (Figure 36) is inconclusive with value ranging from 55 to 245 ms. Thus this result is not more discussed.

In that respect, it cannot be asserted that the visual feedback affect the temporal accuracy.

6.2 Action for vision : role of proprioception in eye tracking

The passive movements are used to study the role of proprioception in eye tracking (Figure 37). Thus, four conditions are used: two conditions with curve trajectories (H and I) and two others with straight line movements (E and F). During these trials, the goal is always the same, follow the centre of the hand (the handle) with the eyes when the handle is moved by the KINARM robot. Sometime, the visual feedback is plotted (white dot) to help and next time not. Henceforth the hand and the target are confused[6] in these conditions. That is why, only the eyes movement in relation to the target is studied in this subsection.

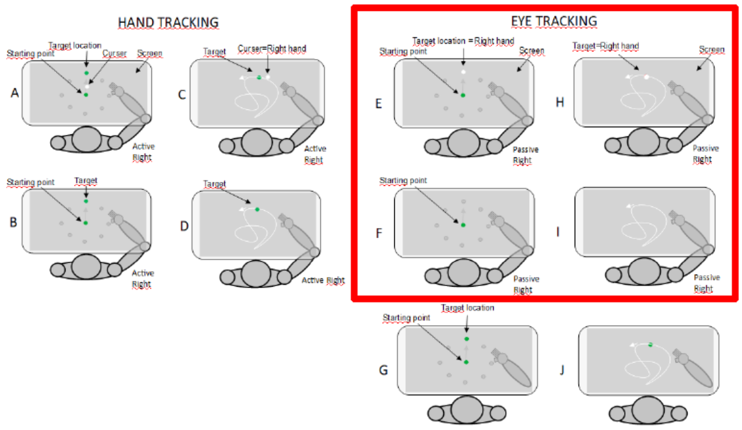

Figure 37: Red frame: four conditions used to study the role of proprioception in eye tracking.

6.2.1 Typical trials

One more time, before analysing the role of proprioception in eye tracking with values, it is interesting to illustrate typical trials.

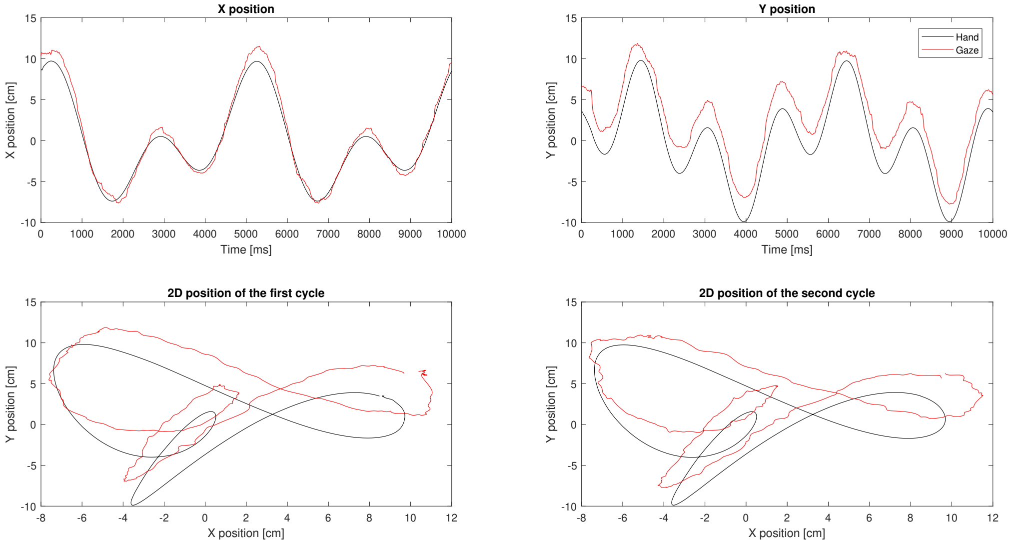

Figure 38: A typical trial of condition H where the hand (black line) is the target.

Firstly, the **condition H** is represented on the figure 38 where the participant follow with eyes his hand moved by the robot with curve trajectories. The visual feedback (white

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[6] The target is the hand.

dot) is plotted on the black screen to help. Despite an upper shift, the eye movement (red line) seems to correctly follow the target (black line) which is the visual feedback of the hand. It will be checked in next sub-sub-sections but red line seems to be not shifted to the left or the right compared to the target (hand).

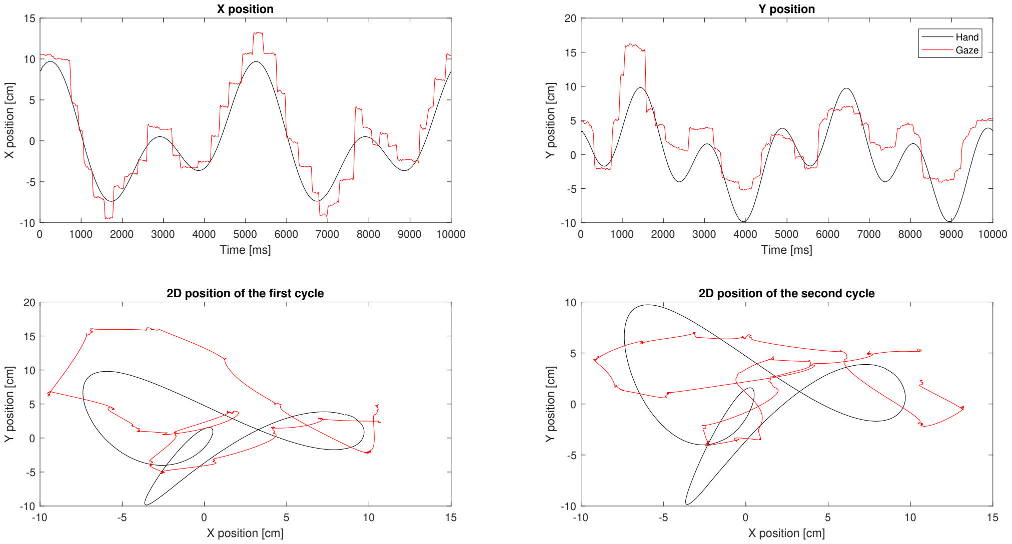

Figure 39: A typical trial of condition I where the hand (black line) is the target.

Concerning the second typical trial for **condition I** with passive and curve trajectories, the gaze path (red line) on figure 39 seems to be completely different. For starters, it is observed that the 2D position of the gaze does not follow the invisible target very well. Then for the x position (upper left graph), it is possible to observe that the eye signal is well modulated in relation to the target with the help of many saccades. The same observation is done for the y position but with an amplitude problem. It is worth mentioning that it is a very good trial because in a lot of trials, the eye path is not as similar as the target's. In the graph of the y-position, the gaze (red line) seems to be shifted to the left. The analysis about saccades will be realised in the other sub section 6.6.

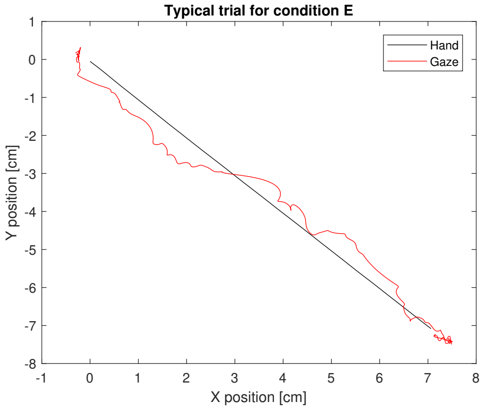

Figure 40: A typical trial of condition E where the hand is the target.

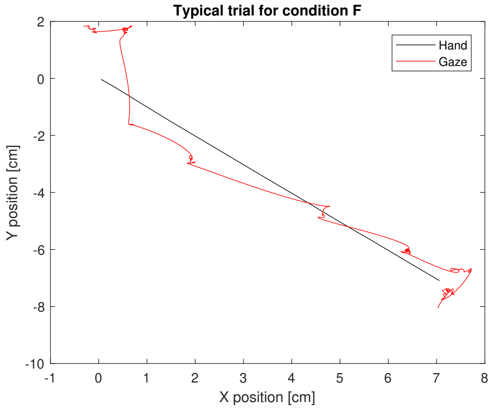

Figure 41: A typical trial of condition F where the hand is the target.

Finally, the typical trials for **condition E** (Figure 40) and for the **condition F** (Figure 41) are similar to the two previous conditions for 2D position.

6.2.2 Is visual feedback necessary for spatial accuracy?

One question is to know if the visual feedback influences the spatial accuracy of the gaze according to the target. One more time, to answer this issue, the position error analysis between eye and target is used (Figure 42). Thus, for conditions with curve trajectories (H and I), it is observed that the position error increase when the participant has only the proprioception sensors to know the position of the hand (p-val $= 2.1756 \cdot 10^{-8}$). The same observation is done with the straight line movements (p-val $= 0.0082$).

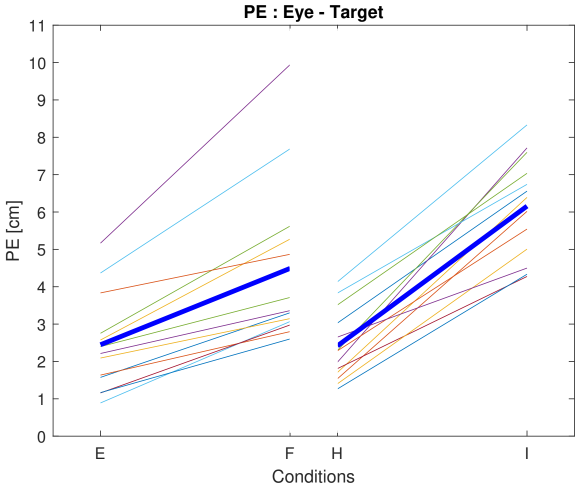

Figure 42: Mean position error between eyes and target by passive condition. The thick blue lines are the mean value of all subjects.

This way, the visual feedback of the hand increases the spatial accuracy in both kinds of trajectories. In addition, it can be noticed that the difference between the position error of conditions with straight line paths and curve trajectories is not visible.

6.2.3 Does the visual feedback have an influence on the tracking speed?

To answer this question, the figure 43 shows that there is an increase of the smooth pursuit velocity error when the visual feedback is not plotted during trials with curve trajectories (condition I). This increase is statistical significant with a p-value of $4.1268 \cdot 10^{-7}$ and is explained by strategies of the eyes to make lot of large saccades. Indeed, only the smooth pursuit parts of the signals are used so the peaks of saccades do not disrupt data and it is observed that the eyes movement is pretty linear between these saccades.

Concerning the straight line paths, the presence of the visual feedback seems to not impact the smooth pursuit velocity error (p-val $= 0.3932$). Moreover, the two upper lines seem to be outliers and if these were ignored, the thick blue lines would be even more horizontal. This lack of impact of the visual feedback can be explained by the highly predictable nature of the path, thus the participant uses saccades to correct the position but the dynamic is well inked in its strategy of pursuing.

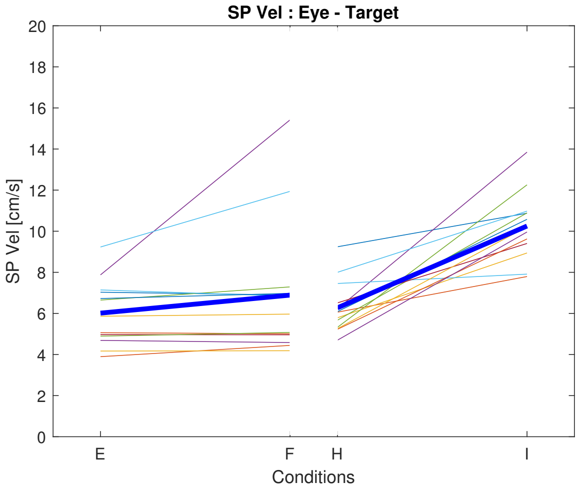

Figure 43: Mean smooth pursuit velocity error between eye and target. The thick blue lines are the mean value of all subjects.

6.2.4 Is visual feedback necessary for temporal accuracy?

While the data of active movements did not bring much information about the temporal accuracy, these conditions give more information about the role of proprioception for temporal accuracy in eye tracking.

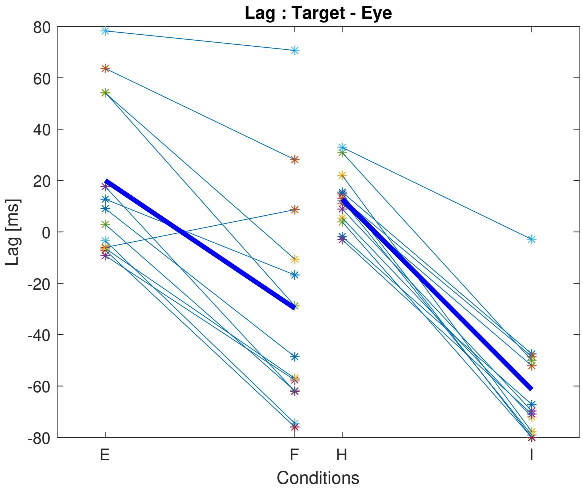

Figure 44: Mean lag between target and eye for passive conditions. The thick blue lines are the mean value of all subjects.

Indeed, for the condition H with visual feedback of the hand and curve trajectories, it is observed (Figure 44) that the lag is closed to zero (between 0 and 20 ms for ten of the participants). So even if there are position errors, these errors are not due to a temporal accuracy but it is induced by a position shift (see y-position in figure 38) or a difference in the amplitudes of trigonometric function of the trajectories. Then, for the condition I when the visual feedback disappears, the lag values are really different compared to the previous condition (p-val $= 6.7813 \cdot 10^{-11}$). Indeed the lag becomes negative with value between -40 and -80 ms which means that the participant try to anticipate the trajectory of the target (hand). This negative lag confirms the left shift of the gaze compared to the target observed on the typical trial.

The same observation is done with the straight line paths with values close to zero when the visual feedback is plotted and negative values when the participants have only proprioception sensors to know the position of the target. In these two last conditions, five participants seem to have abnormal values.

6.3 Role of hand proprioception

Two other conditions can be added to observe the role of hand proprioception in eye tracking. One condition for straight line paths and another one for curve trajectories and are respectively the condition G and the condition J (Figure 45). During these conditions only eyes track the target (hands at rest). The main goal is to observe if the spatial and temporal accuracy are impacted when the target and the hand are confused.

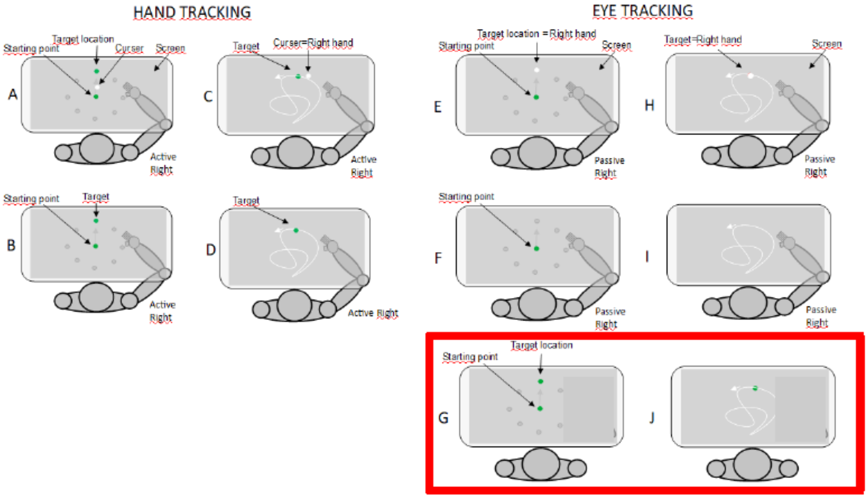

Figure 45: Red frame: Two added conditions used to study the role of proprioception in eye tracking

The analysis of these two new conditions will not be detailed in this subsection 6.3 but in the subsection 6.5 of comparison between straight line paths and curve trajectories. Thus, only the typical trials are described here.

6.3.1 Typical trials

Once again, it is interesting to illustrate typical trials.

Concerning the **condition J** with only eyes tracking of curve trajectories, a typical trial is shown in the figure 46. Despite the bad start of the eye tracking (first 200 ms), the shape of the 2D position line of eye is similar to that of the target. The same observation can be done with the x and y positions. Furthermore, the gaze (red line) seems to be shifted to the right compare to the target (green line).

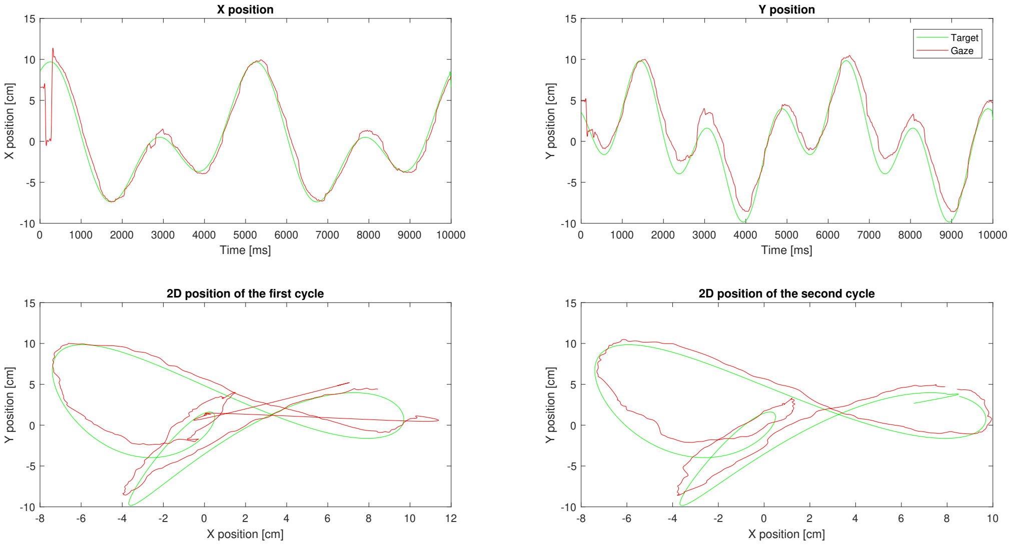

Figure 46: A typical trial of condition J.

Then, for the **condition G** with straight line paths, the gaze line fit well the target trajectory (Figure 47).

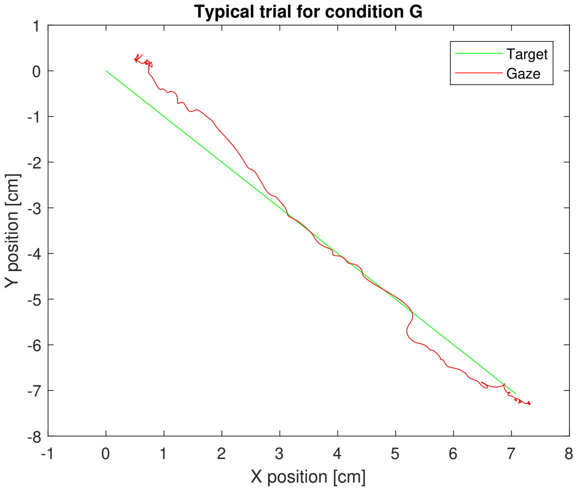

Figure 47: A typical trial of condition G.

6.4 Compare right vs left hand in tracking

To study the impact of the hand used, only conditions involving straight line movements of the hand are repeated. Thus the condition of active movements A and B as well as the condition of passive movements E and F are reiterated with the left hand. These new conditions are respectively named AL, BL, EL and FL. The main goal is to observe if the spatial and temporal accuracy of the gaze are impacted by the hand used. We will see that the hand used does not change the behaviour of the eyes trajectories on the following analysis.

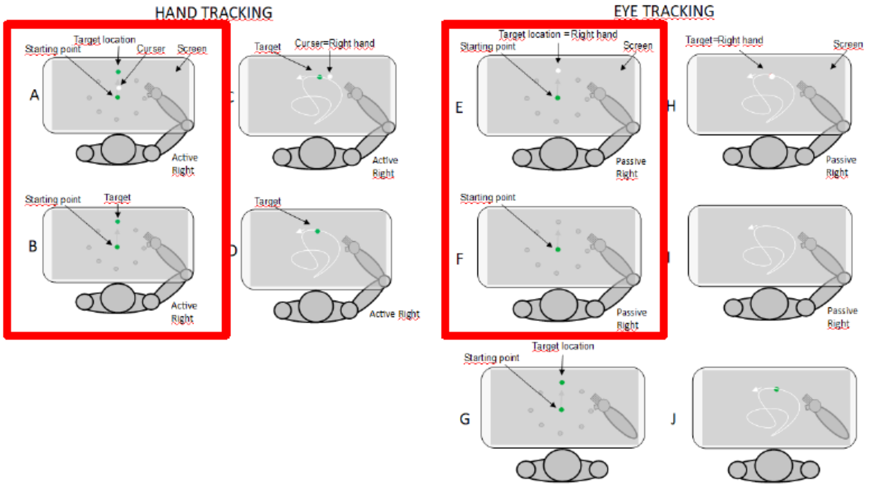

Figure 48: Red frame: four conditions repeated with the left hand.

6.4.1 Does the hand used have an influence on the spatial accuracy?

Directly, it is observed in the figure 49 that the means of a condition with the right hand are similar to its counterpart with the left hand. This is confirmed by the no rejection of the null hypothesis of equality of means between homologous conditions (p-val>0.05 on table 2).

	A - AL	B - BL	E - EL	F - FL
p-val	0.9685	0.8657	0.4345	0.9012

Table 2: P-values of t-test on equality of means between homologous conditions for position error.

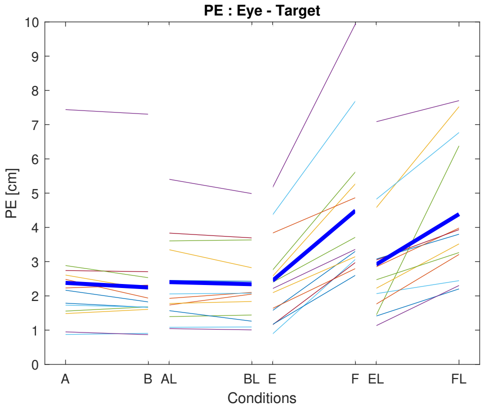

Figure 49: Mean position error between eyes and target by conditions. The thick blue lines are the mean value of all subjects.

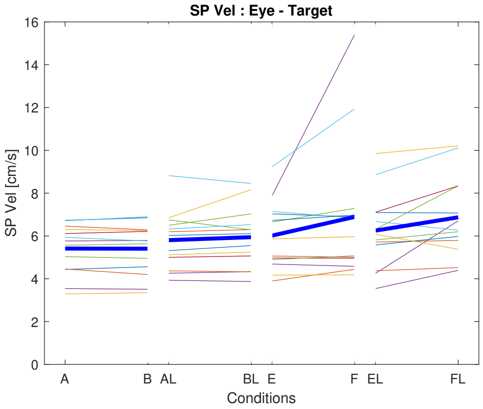

Figure 50: Mean smooth pursuit velocity error between eye and target. The thick blue lines are the mean value of all subjects.

6.4.2 Does the hand used have an influence on the tracking speed?

One more time, it is observed that the hand used does not affect this second parameter that is the smooth pursuit velocity error (Figure 50). These observations can be confirmed by table 3 which presents p-values greater than 0.05.

	A - AL	B - BL	E - EL	F - FL
p-val	0.4306	0.3033	0.7234	0.9844

Table 3: P-values of t-test on equality of means between homologous conditions for smooth pursuit velocity error.

6.4.3 Does the hand used have an influence on the temporal accuracy?

Finally, the answer to this last question is still negative. This can be observed on the figure 51 and by the p-values of the table 4.

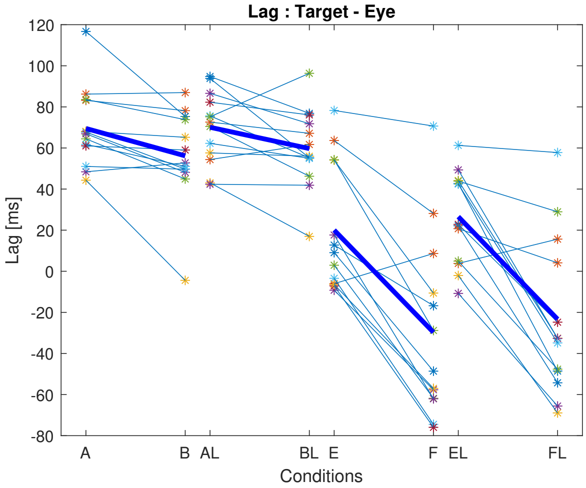

Figure 51: Mean lag between target and eye. The thick blue lines are the mean value of all subjects.

	A - AL	B - BL	E - EL	F - FL
p-val	0.9372	0.6729	0.5454	0.6993

Table 4: P-values of t-test on equality of means between homologous conditions for lag.

6.5 Compare different trajectories: straight lines, curves

In this subsection, the impact of the path is analysed. More specifically, does predictability of trajectory have an influence on the different parameters of the vision? Furthermore, the role of hand proprioception is studied with the two additional conditions G and J of the subsection 6.3 (Role of hand proprioception).

6.5.1 Does the predictability of the trajectories have an influence on the spatial accuracy?

Firstly, we can compare the figures 52 and 53 to realise that the shape of the two graphs are similar. Henceforth, it can be concluded that the strategy used by the eyes to follow the target is independent of the trajectories of the target but changes with the condition of the trial.

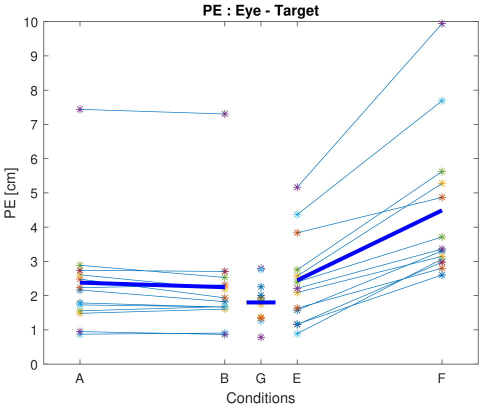

Figure 52: Mean position error between eyes and target by conditions with straight line paths. The thick blue lines are the mean value of all subjects.

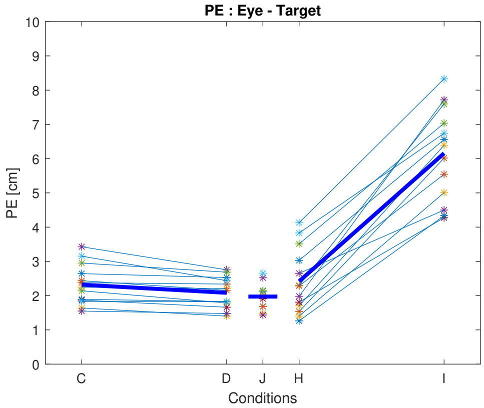

Figure 53: Mean position error between eye and target with curve paths. The thick blue lines are the mean value of all subjects.

However, even if the strategy of gaze pursuit is the same regardless of the trajectory, it is interesting to perform a test of equality of means (t-test) between corresponding conditions. Thus, only one statistical significant difference in equality of means between condition F and I is observed (Table 5 : p-val < 0.05). Therefore, the position error does not depend on the trajectory with the exception of one condition with passive movements without the visual feedback. So, when the participant only has the proprioception sensors to know the position of the hand, the position error increases with the difficulty to predict the trajectory. Indeed, in the sub-sub-section 6.2.4, we observed that participants attempt to predict the hand position in these two conditions and that would explain why those are the only conditions impacted by the trajectory for spatial accuracy.

	A - C	B - D	G - J	E - H	F - I
p-val	0.903	0.7284	0.3796	0.948	**0.0284**

Table 5: P-values of t-test on equality of means between homologous conditions (straight lines vs curve paths) for the position error.

6.5.2 Does the proprioception have an influence on the spatial accuracy of the gaze when the target is plotted?

It is observed that the active or passive movements of the hand during tasks have not any influence on the spatial accuracy (position error) of the gaze when the goal is to follow a plotted target (Figures 52 and 53). Indeed, when it is asked to follow the target with the eyes and with the hand, the second task does not seem to interfere with the first one (conditions B-G and D-J). Then, the fact that the target becomes the hand which moves passively does not improve the spatial accuracy of the gaze (conditions D-J and H-J). Naturally, it would be expected an increase in the accuracy of vision with the addition of the proprioception sensors but this is not the case. These observations are confirmed by p-values of the table 6.

	B - G	E - G	D - J	H - J
p-val	0.3596	0.1169	0.4939	0.1259

Table 6: P-values of t-test on equality of means between conditions with and without hand for position error.

6.5.3 Does the predictability of the trajectories have an influence on the tracking velocity?

In contrast with the position error, the smooth pursuit velocity error is impacted by the kind of trajectories used (Figures 54 and 55).

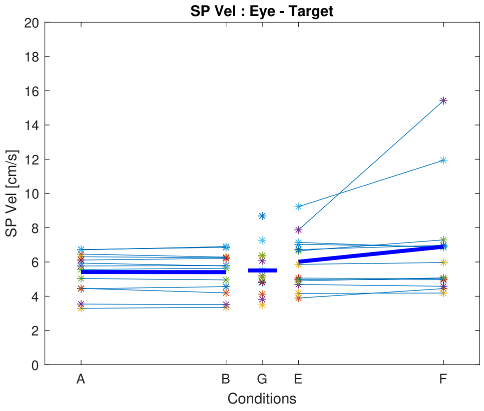

Figure 54: Mean smooth pursuit velocity error between eyes and target by conditions with straight line paths. The thick blue lines are the mean of all subjects.

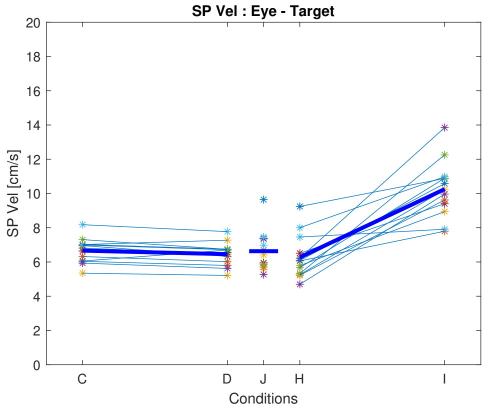

Figure 55: Mean smooth pursuit velocity error between eye and target with curve paths. The thick blue lines are the mean value of all subjects.

First of all, with curve trajectories, a rise of smooth pursuit velocity error is observed when the visual feedback of the passive hand movement disappears (conditions H-I). This observation is not the same with straight line movements of conditions E and F.

Then, the smooth pursuit velocity error seems to be bigger with curve paths. This is confirmed by the p-values of the table 7 except for the conditions E and H (p-val = 0.6505). However, this result should be carefully taken because this can be partly explained by the difference of velocity range between the two kinds of trajectories. Indeed, the mean velocity during the curve trajectory is 16 cm/s when it is only 5 cm/s for the straight line movement.

	A - C	B - D	G - J	E - H	F - I
p-val	**0.0031**	**0.0108**	**0.039**	0.6505	**0.003**

Table 7: P-values of t-test on equality of means between homologous conditions (straight lines vs curve paths) for smooth pursuit error.

6.5.4 Does the proprioception have an influence on the tracking velocity?

In figures 54 and 55, it is shown that there is not any statistical significant difference of the smooth pursuit velocity error between conditions B, G and E or between condition D, J and H (p-values on table 8). Thus, the proprioception does not improve the adaption of velocity for the eye tracking.

	B - G	E - G	D - J	H - J
p-val	0.8482	0.399	0.6462	0.4631

Table 8: P-values of t-test on equality of means between conditions with and without hand for the smooth pursuit velocity error.

6.5.5 Does the predictability of the trajectories have an influence on the temporal accuracy?

By comparing the two figures 56 and 57 several differences in the lag can be observed between the two kinds of trajectories. Firstly, during active movements, the lag is bigger with curve trajectories. Then, a difference for the conditions with only eyes will be explained in the next question (sub-sub-section 6.5.6). Finally, even if the values for condition E and F do not seem to be very reliable (high variances), the mean values of H is close to the mean of E (p-val = 0.4341) and the prediction (negative lag) in condition I is more important than with the condition F.

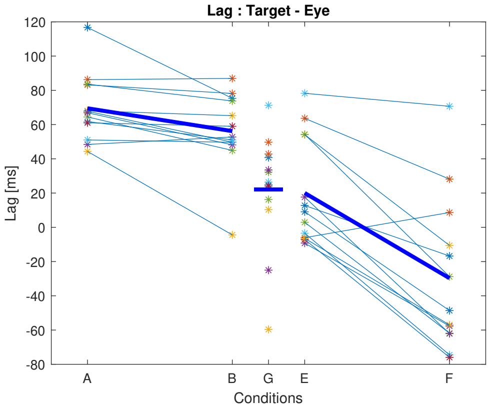

Figure 56: Mean lag between eyes and target by conditions with straight line paths. The thick blue lines are the mean value of all subjects.

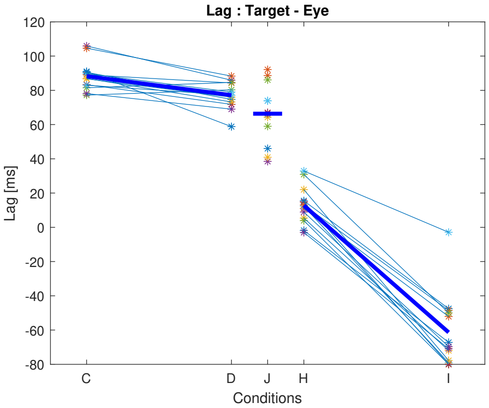

Figure 57: Mean lag between eye and target with curve paths. One colour dot by subject. The thick blue lines are the mean value of all subjects.

These observations are confirmed by the p-values of the table 9. Thus, the unpredictability of the trajectory has an influence on the temporal accuracy.

	A - C	B - D	G - J	E - H	F - I
p-val	**0.0039**	**0.0044**	**0.0003**	0.0.4341	**0.0294**

Table 9: P-values of t-test on equality of means between homologous conditions (straight lines vs curve paths) for lag.

6.5.6 Does the proprioception have an influence on the temporal accuracy?

For straight line movements (Figure 56), the mean lag of condition G is close to the condition E of passive movement with visual feedback (p-val = 0.8705). Thus, in this case the proprioception of the hand does not improve the mean lag that is close to 20 ms. However, the lag is damaged by the fact of making a second related task which is to follow the same target with the active movement of the hand (condition B).

Conversely, the lag of condition J is close to the condition D of the active movement without visual feedback of the hand (Figure 57). Thus, when the goal is to follow an unpredictable target with the eyes, the second task with the active movement of the hand does not damage the lag. However, this lag can be reduced with the help of the proprioception when it is observed that the mean lag of the condition H is closer to zero.

To support these observations, the different p-values required are in the table 10.

	B - G	E - G	D - J	H - J
p-val	**0.0055**	0.8705	0.0513	$\mathbf{1.43} \cdot 10^{-9}$

Table 10: P-values of t-test on equality of means between conditions with and without the hand for lag analysis.

6.6 Saccades analysis

As mentioned in the state of the art (sub-sub-section 2.1.1), saccades can be characterised by some parameters like amplitudes, rates ... Moreover, we always observed with typical trials that a participant makes more saccades with big amplitudes during conditions of passive movements without visual feedback. Thus, in this sub-section, an analysis of saccades is done according to conditions with the straight lines and curve paths.

6.6.1 Does the amplitude of saccades change according to conditions?

Directly, it is observed that the shapes of the two graphs (Figures 58 and 59) are identical with an increase of the amplitude during passive movements of the hand without visual target (conditions F and I). Thus, when the only piece of information comes from the proprioception, the participant makes saccades with bigger amplitudes. Then, when the target is plotted on the screen, there is no statistical significant difference between the other conditions (p-values on table 11) with the exception between conditions D and J.

Henceforth, for the curve trajectory when it is asked to also follow the target with active movements (conditions C and D), it would appear that the participant makes saccades with smaller amplitudes compared to condition J with only eye tracking. This observation is not made with straight line movements.

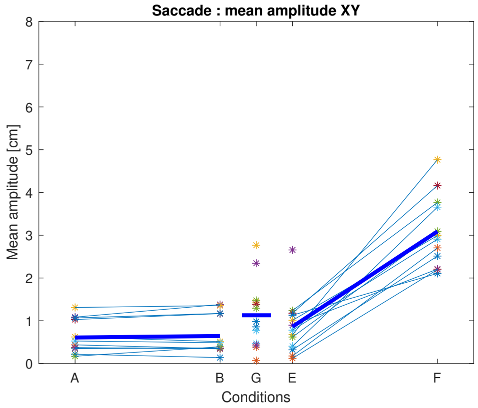

Figure 58: Mean amplitude of saccades according to conditions with straight line paths.

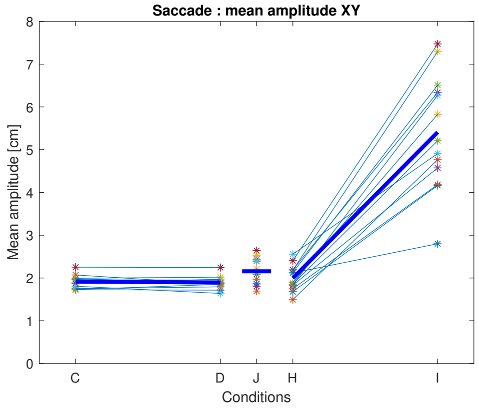

Figure 59: Mean amplitude of saccades according to conditions with curve trajectories.

	A - B	B - G	G - E	E - F	C - D	D - J	J - H	H - I
p-val	0.8298	0.0632	0.0355	**1.57e-7**	0.7181	**0.0103**	0.1856	**4.89e-9**

Table 11: P-values of t-test on equality of means amplitudes between conditions with same kind of trajectories.

6.6.2 Does the rate of saccades change according to conditions?

The rate of saccades represents the number of saccades by second. Thus, the rate of saccades for a trial is the number of saccades divided by the duration of the trial[7].

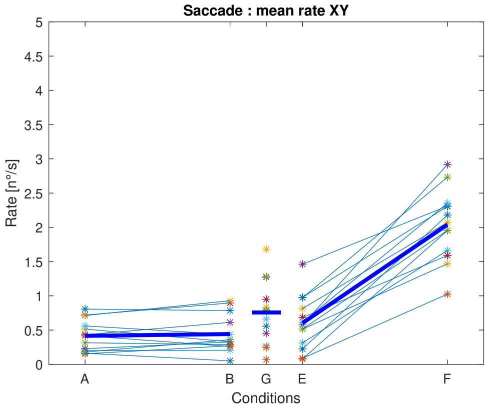

Figure 60: Mean rate of saccades according to conditions with straight line paths.

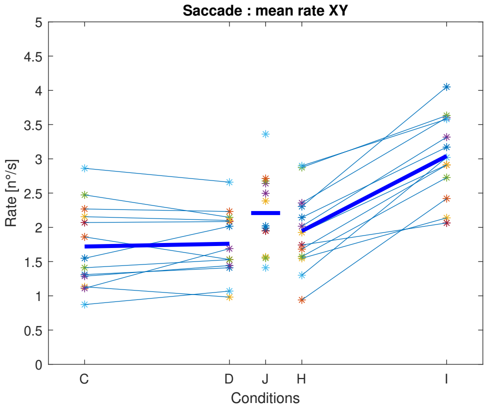

Figure 61: Mean rate of saccades according to conditions with curve trajectories.

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[7] The time of the trial minus the duration of blinks or bad data.

The observations concerning the amplitude are identical for the rate with an added statistical significant difference between conditions B and G (Table 12). Henceforth, the shapes of the two graphs on figures 60 and 61 seems to be identical. Thus, the rate increases with conditions where only the proprioception sensors can help to know where is the target. Then, it is observed that the rate of saccades is smaller with the second tasks of following the target with active movements of the hand compared to the condition with only eye tracking.

	A - B	B - G	G - E	E - F	C - D	D - J	J - H	H - I
p-val	0.7924	**0.0453**	0.3665	**3.35e-8**	0.8529	**0.0406**	0.2508	**7.85e-5**

Table 12: P-values of t-test on equality of means rate between conditions with same kind of trajectories.

6.6.3 Does the percents of saccades distance XY change according to conditions?

The percents of saccades distance XY are proportionate to the mean amplitude and the rate of saccades. So, the observations are the same as with mean amplitudes of saccades (Table 13). During condition I, it is observed that more that half of the distance is covered by saccades (Figure 63). This percent is close to 40% for condition F (Figure 62). Concerning the condition J, it seems that the participant travels more distance with saccades that when he also has to follow the target with his hand. Finally, the contribution of the proprioception during passive movements with the visual target is not conducive to smooth pursuits.

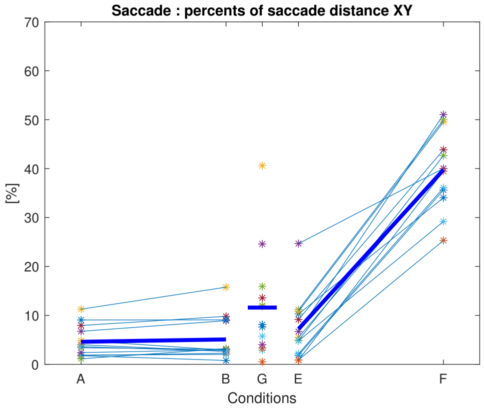

Figure 62: Mean percents of saccades distance XY according to conditions with straight line paths.

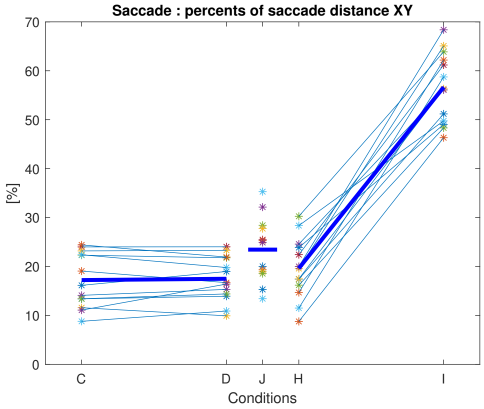

Figure 63: Mean percents of saccades distance XY according to conditions with curve trajectories.

	A - B	B - G	G - E	E - F	C - D	D - J	J - H	H - I
p-val	0.7498	0.0568	0.2227	**2.58e-11**	0.8942	**0.0126**	0.1398	**5.12e-13**

Table 13: P-values of t-test on equality of means percents of saccades distance XY between conditions with same kind of trajectories.

6.6.4 Does the predictability of the trajectories have an influence on saccadic circuit?

As we observed, the shape of the graphs for saccades analysis are similar between straight line paths and curve trajectories. However the different values are always bigger for homologous conditions for curve trajectories and it is confirm by p-val on the table 14. Thus, the predictability of the trajectories has an impact on saccadic circuits and is more conducive to smooth pursuits.

	A - C	B - D	G - J	E - H	F - I
p-val (amplitude)	**2.73e-11**	**1.09e-8**	**7.94e-6**	**3.76e-5**	**0.0002**
p-val (Rate)	**1.76e-7**	**1.19e-8**	**3.29e-7**	**0.0001**	**1.96e-7**
p-val (Percents)	**2.47e-7**	**2.78e-7**	**4.28e-5**	**36.96e-6**	**0.0025**

Table 14: P-values of t-test on equality of means for different parameters of saccades between homologous conditions.

6.7 Reaction time

The reaction time of the hand or the eyes, is the time of visible reaction after the first stimulus[8]. Here, it will be analysed the influence of conditions and paths on the reaction time.

6.7.1 How the reaction time of eyes is affected by the different conditions?

To compute and detect the reaction time of eyes for conditions with curve paths, a threshold on the velocity of 25 cm/s is used because it is observed in this case that the eye movement is initialised by a saccade. Concerning the reaction of eyes for conditions with straight line movements, it is more complicated because the target starts to move from zero speed with a small acceleration. Thus, we try to detect when the gaze is out of the starting point.

Thus, with the difficulty to detect the reaction time with straight line conditions, it is observed on the figure 64 that no conclusion can be reached.

Concerning the reaction time of conditions with curve paths (Figure 65), some observations are possible. Firstly, it is observed with active movements that the reaction time decreases when the visual feedback of the hand is not plotted. This can be explained by the fact that the visual feedback of the hand disappears when the target starts to move

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[8] Time 0: start of the movement of the target or/and the handle.

which might be a stimulus more noticeable. Then, when the condition is to follow the green target with only eyes, the reaction time seems even smaller. Indeed, the subject needs to be concentrated on one task only. Finally, this reaction time of the eyes can be reduced one last time thanks to the contribution of the proprioception during the condition with passive movements and the visual feedback. This reaction time corresponds to the normal latency of 200 ms after stimulus occurrence of a saccade observed in the sub-sub-section 2.1.1. However, during conditions with passive movements, the reaction time increases when the visual feedback is not plotted and that there is only the proprioception to detect the start of movements.

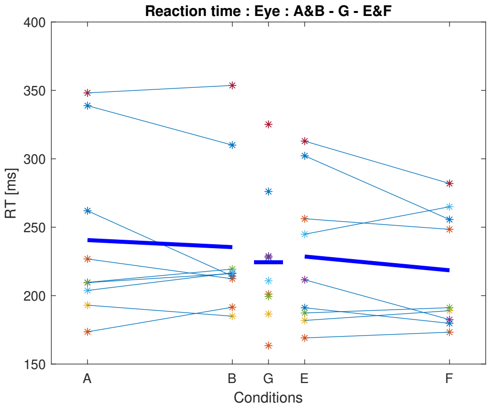

Figure 64: Reaction time of the eyes according to conditions with straight line movements.

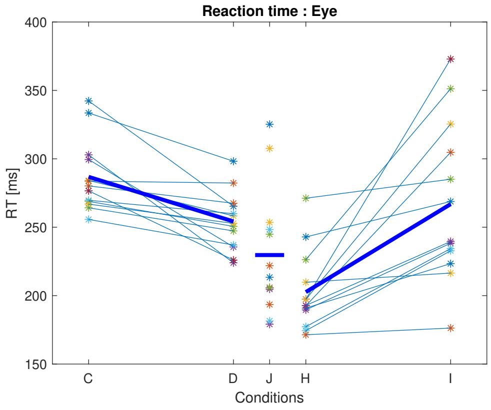

Figure 65: Reaction time of the eyes according to conditions with curve movements.

6.7.2 How the reaction time of hand is affected by the visual feedback during conditions with active movement?

The reaction time of hand can be observed in the figures 66 and 67. These reaction times seem to be similar at the reaction time of the eyes. However, none conclusion can be drawn with these graphs.

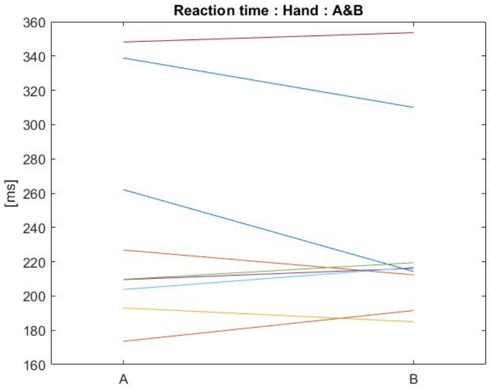

Figure 66: Reaction time of the hand according to active conditions with straight line movements.

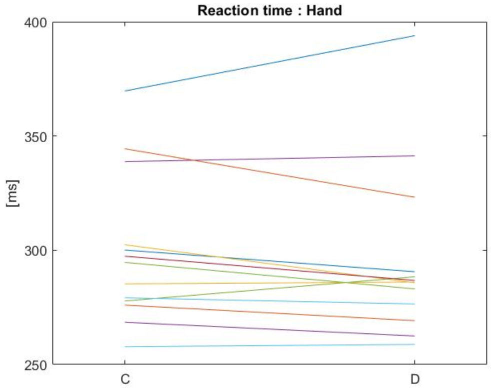

Figure 67: Reaction time of the hand according to active conditions with curve movements.

6.8 Splitting of the lag

One question for the lag of curve trajectories is to know if the 2D lag is more impacted by the lag on x-axis or y-axis.

Concerning the lag of the eyes, it is observed on the figure 68 that the lag is bigger on y-axis for the two conditions with active movements and the condition of eye tracking with only eyes. Then, for the two conditions with passive movements there is no statistical difference. This can be confirmed by the p-value of the table 15.

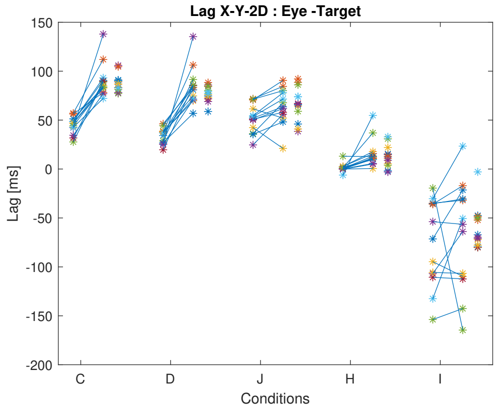

Figure 68: Splitting of the lag according x- and y-axis for eye signals of curve trajectories. The left of a line reflects the lag on x-axis, the right of a line represents the lag on y-axis and a isolate point is the 2D lag according to conditions.

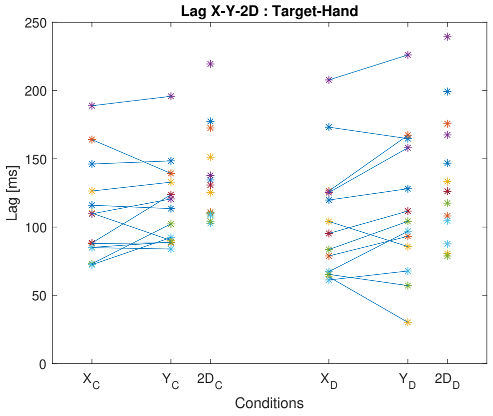

Figure 69: Splitting of the lag according x- and y-axis for eye signals of curve trajectories. The left of a line reflects the lag on x-axis, the right of a line represents the lag on y-axis and a isolate point is the 2D lag according to conditions.

For the lag of the hand (Figure 69), no information can be obtained concerning the difference between the lag on x-axis or y-axis.

	C	D	J	H	I
p-val	**9.84e-9**	**7.04e-9**	**0.0022**	0.6943	0.0731

Table 15: P-values of t-test on equality between means of x lag and y lag

6.9 Position error with lag compensated

If "lag" is true lag, then the lag compensated error will be less than the actual one. Otherwise it adds some uncertainty. In this subsection, it will be observed if it is the case with the gaze lag and with the hand lag. To obtain this new position error, the eye (hand) signals are staggered depending on the corresponding lag, then the position error is recalculated.

Concerning the new position error between eye and target with lag compensated for curve trajectories (Figure 71), it appears that this one is smaller for conditions with active movements or with only eyes. However, for conditions with passive movements (H and

I), the lag seems to be less correct because the decrease of the new position error is not statistical significant. It is not true for the condition H because it is observed in previous section that the lag is very small for this condition (0-20ms). So, the compensated lag does not shift the position and it is normal to not observe a p-values smaller than 0.05. In support of these observations, the table 16 gives the needed p-values and it is possible to compare the figure 71 with the figure 53 of the sub-sub-section 6.5.1.

	C	D	J	H	I
p-val	**0.049**	**0.0274**	**0.0046**	0.7403	0.2205

Table 16: P-values of t-test on equality between means of the position error and the new position error with the lag compensated for conditions of curve trajectories.

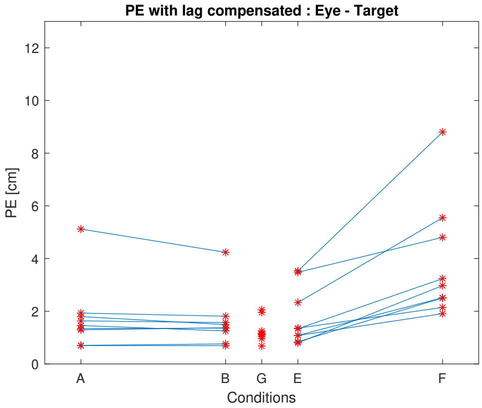

Figure 70: New position error (with the lag compensated) between the eye and the target for conditions with straight line trajectories.

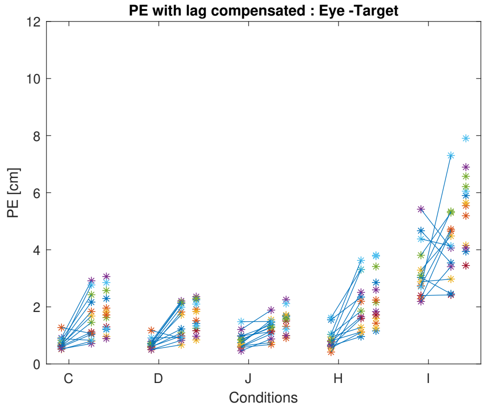

Figure 71: New position error (with the lag compensated) between the eye and the target for conditions with curve trajectories.

For straight line conditions, the new position error with the compensated lag between the eye and the target can be observed on the figure 70. Compare to the figure 52, it is appears that the new position error is smaller for each conditions with a decrease of approximately 1 cm. However, even if it is visible on graphs, these differences are not statistically significant (p-val $>$ 0.05).

Concerning the new position error between the hand and the target with the compensated lag, it is perceived on the figures 72 and 73 that the new position error is smaller thanks to the compensation of the lag (comparison with the figure 31). This observation is reinforced by t-test shown in the table 17 except for the condition D.

	A	B	C	D
p-val	**0.0051**	**0.0176**	**0.0406**	0.1733

Table 17: P-values of t-test on equality between means of position error and the new position error with the lag compensated for conditions with active movements.

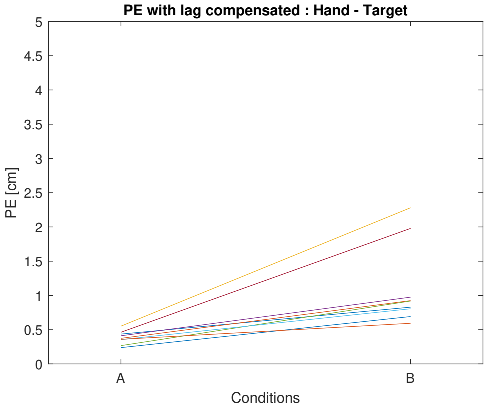

Figure 72: New position error (with the lag compensated) between the hand and the target for conditions (A and B) with straight line trajectories.

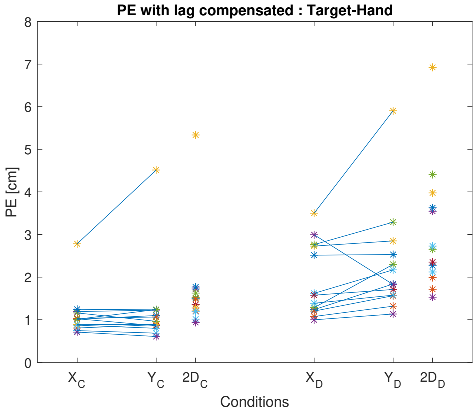

Figure 73: New position error (with the lag compensated) between the hand and the target for conditions (C and D) with curve trajectories.

Finally, the figure 74 illustrates that the new position error with the compensated lag is always better. Indeed, for each red point (PE) it is observed that the corresponding blue point (PE with the compensated lag) is always smaller.

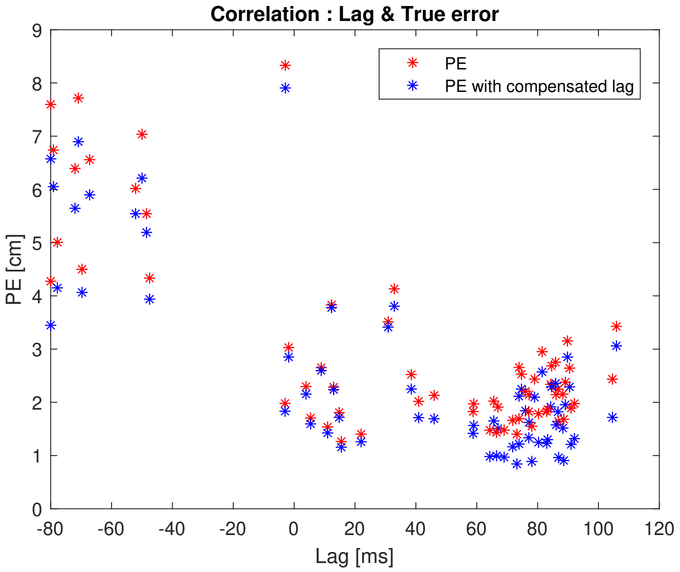

Figure 74: Correlation between the lag and the position error in red. In blue the correlation between the lag and the position error with the compensated lag.

6.10 Role of the direction

The last main question we would like to answer is whether the direction of the target influences the parameters of the eyes or the hand. Indeed, according an article of R.J Beers and al. [58] : *the CNS (Central Nervous System) takes the direction-dependent precision of visual and proprioceptive localization into account when integrating these two types of information.*

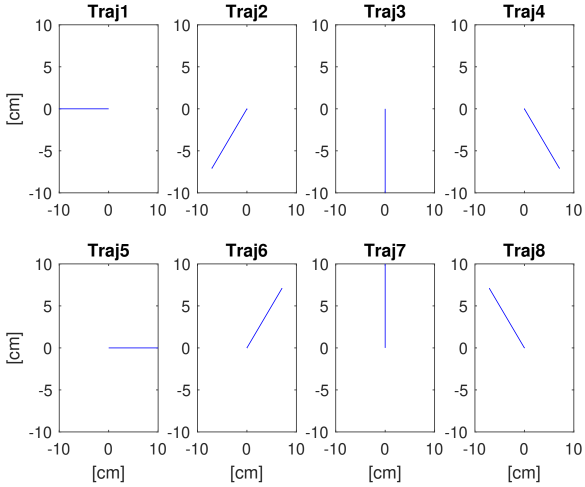

Figure 75: The numbering of the eight trajectories.

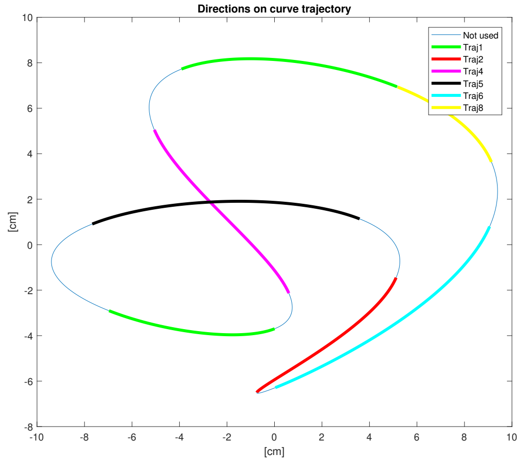

Figure 76: Segments used on the fourth curve path.

Concerning the straight line movements, we separately study the eight different trajectories of the section 3.4.1 (Trajectories). The numbering of the directions is illustrated on the figure 75. Regarding the curve trajectories, some segments of the trial are used to analyse the effect of the eight directions. These segments are detected thanks to the angles of polar coordinates and are only used if their length are longer than 300 ms. Thus, different segments used on the fourth curve path are shown on the figure 76. It is observed on this figure 76 that some parts of the path are not used and that not all of the eight directions are analysed with this curve trajectory.

6.10.1 Does the direction of the target with straight line movement have an influence on the position error of the eyes?

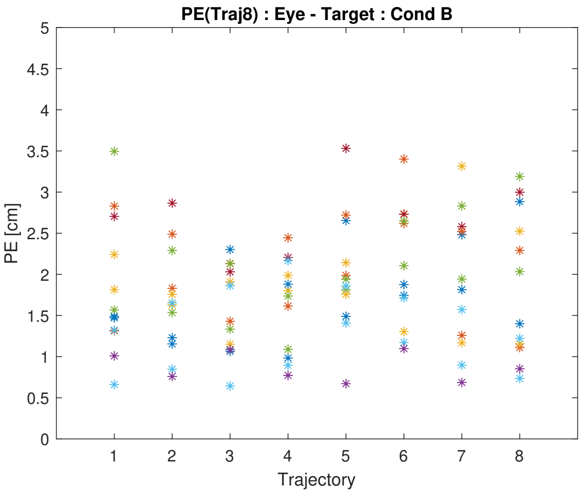

Figure 77: Position error between eye and target according to directions for the condition B.

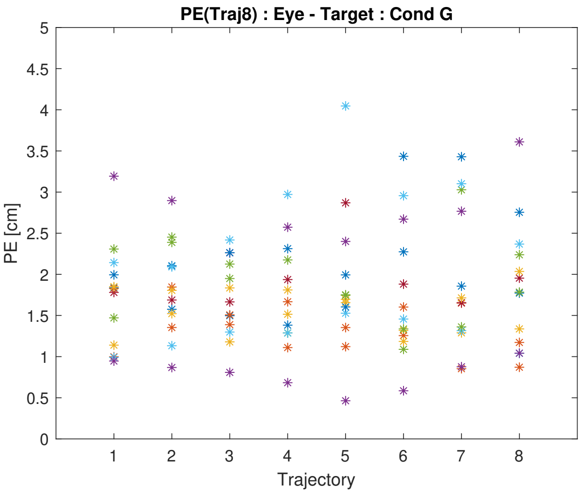

Figure 78: Position error between eye and target according to directions for the condition G.

Firstly, the position error of the eyes seems not to be influenced by the direction of the target. This can be observed on the figures 77 and 78 for the conditions B and G. Even tough the trajectories 3 and 4 appear smaller on the figures for the condition B, it is not statistical significant. Here, only the conditions B and G are plotted but the same observation is done for each conditions.

6.10.2 Does the direction of the target with straight line movements have an influence on the position error of the hands?

No difference is detected (p-values > 0.05) about the influence of the directions on the position errors between the hand and the target. This is shown on the figures 79 and 80. One more time, only the conditions B and AL are presented here but the results are similar for all conditions of active movements.

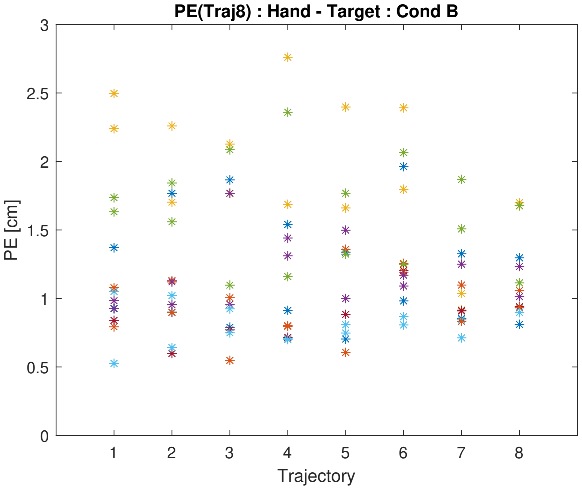

Figure 79: Position error between the right hand and the target according to directions for the condition B.

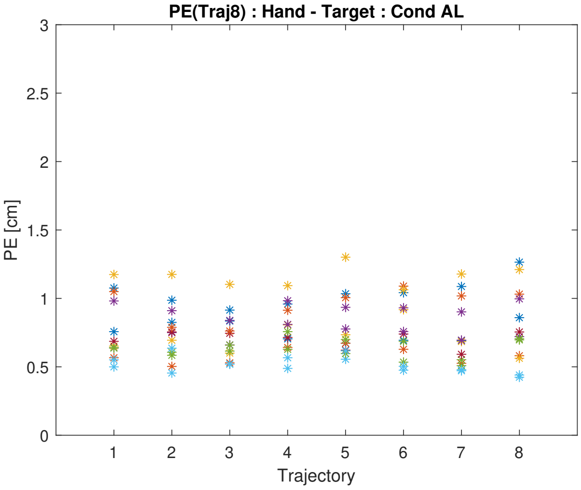

Figure 80: Position error between the left hand and the target according to directions for the condition AL.

6.10.3 Does the direction of the target with straight line movements have an influence on the lag?

Firstly, by looking at the figures 81 and 82 with the lag according directions for conditions B and EL, it is observed that the directions 1, 7 and 8 are more lagging. These 3 directions are in the upper-left quadrant of the vision. During the condition B, there is a movement of the right hand so maybe that this observation can be explained by the fact that the proprioceptive localisation is more accurate in the ipsilateral direction (that occurring on the same side of the body) than in the azimuthal direction [58]. However, the same observation is done with the left hand, therefore this cannot be explained by the proprioception. The reason is that the robot takes the measure of the gaze only on the dominant eye (right for all subjects) and it is harder for the right eye to follow a target in the upper left. On the other hand, the directions (Traj 3, 4 and 5) with the least lag are in the lower right quadrant.

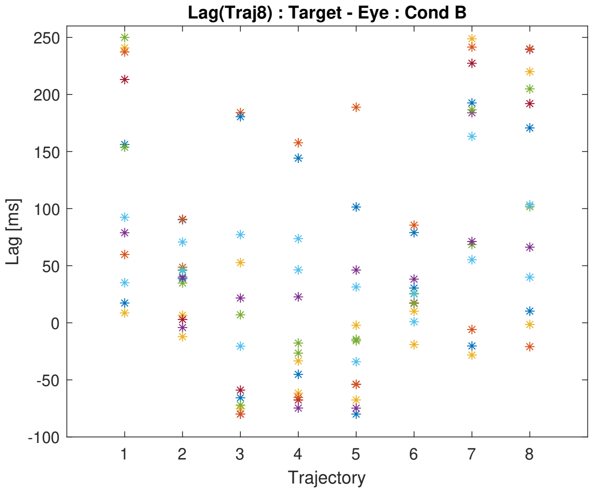

Figure 81: Lag between the eye and the target according to directions for the condition B.

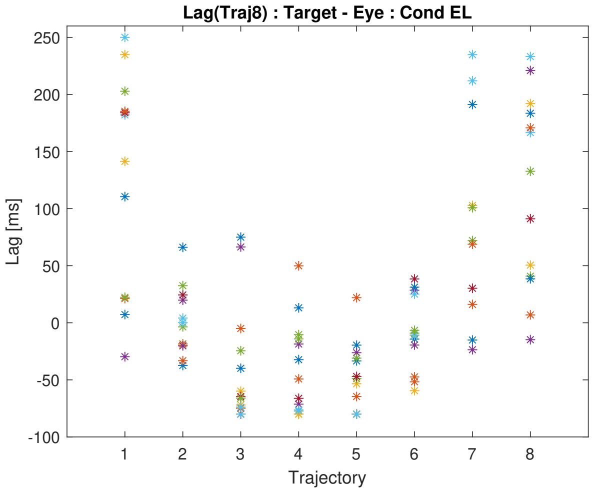

Figure 82: Lag between the eye and the target according to directions for the condition EL.

These observations are supported by the p-values of the table 18 where statistical significant differences are in red. Only the table for the condition B is illustrated in the rapport but all tables look similar.

Traj	1	2	3	4	5	6	7	8
1		0.0029	0.0031	0.0014	0.0008	0.0023	0.8645	0.8298
2			0.2475	0.1638	0.0971	0.4487	0.0099	0.0076
3				0.9674	0.8236	0.4538	0.0060	0.0051
4					0.8415	0.3541	0.0031	0.0025
5						0.2382	0.0019	0.0015
6							0.0079	0.0058
7								0.9706

Table 18: P-values of t-test on equality between means of lag of trajectory X and lag of the trajectory Y for condition B. In red, the statistical significant differences.

6.10.4 Does the direction of the target with curve trajectories have an influence on the lag?

The same observation that with straight line movements is done, the directions 3, 4 and 5 are less impacted by the lag (Figures 83 and 84). One more time, this can be explained by the dominant eye used by the robot and not by the proprioception because the same observation is done between conditions of passive and active movements. The p-values are in the table 19 to reinforce the differences.

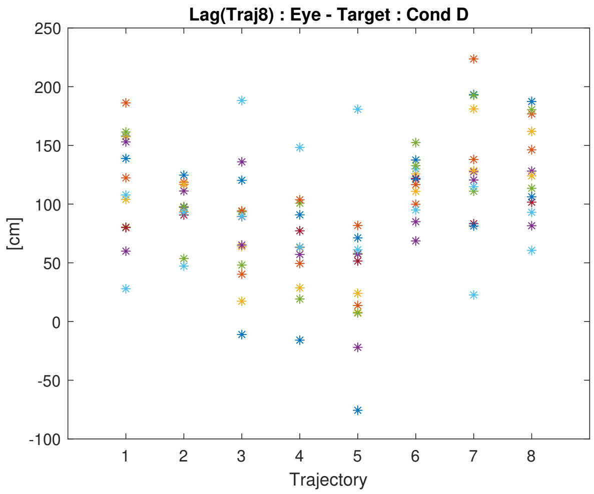

Figure 83: Lag between the eye and the target according to directions for the condition D.

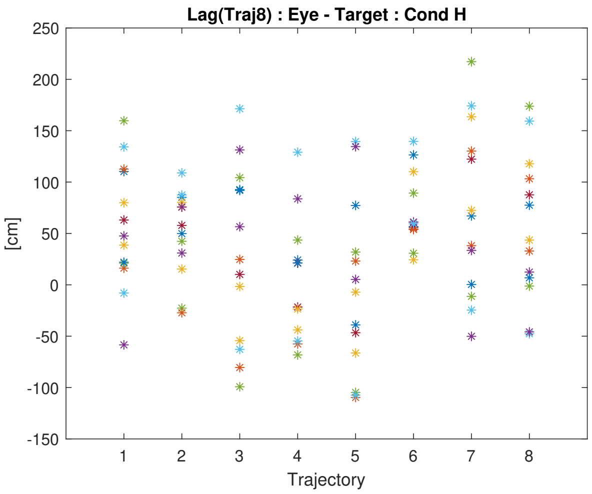

Figure 84: Lag between the eye and the target according to directions for the condition H.

Traj	1	2	3	4	5	6	7	8
1		0.152	0.0571	0.0054	0.0011	0.8334	0.4921	0.5807
2			0.286	0.0257	0.0041	0.0558	0.0432	0.0249
3				0.4461	0.0843	0.0332	0.0192	0.0142
4					0.2222	0.009	0.0018	0.0007
5						0.0003	0.0004	0.0002
6							0.3134	0.3362
7								0.8194

Table 19: P-values of t-test on equality between means of lag of the trajectory X and lag of the trajectory Y for condition D. In red, the statistical significant differences.

7 Discussions

In this section, we will answer several questions to summarise the results and to respond at the aims of the thesis. To help, some links will be done with the theoretical model (Figure 85) proposed on the state of the art (sub-section 2.4). It is the internal model used for conditions with active movements and the visual feedback (VF) as the conditions A and C with loop repetitions of the hand motor system and the eye motor system and the communication (coordination control centre) between them. Some parts of this model is removed with the other conditions and by this way it is possible to better understand the role of these units.

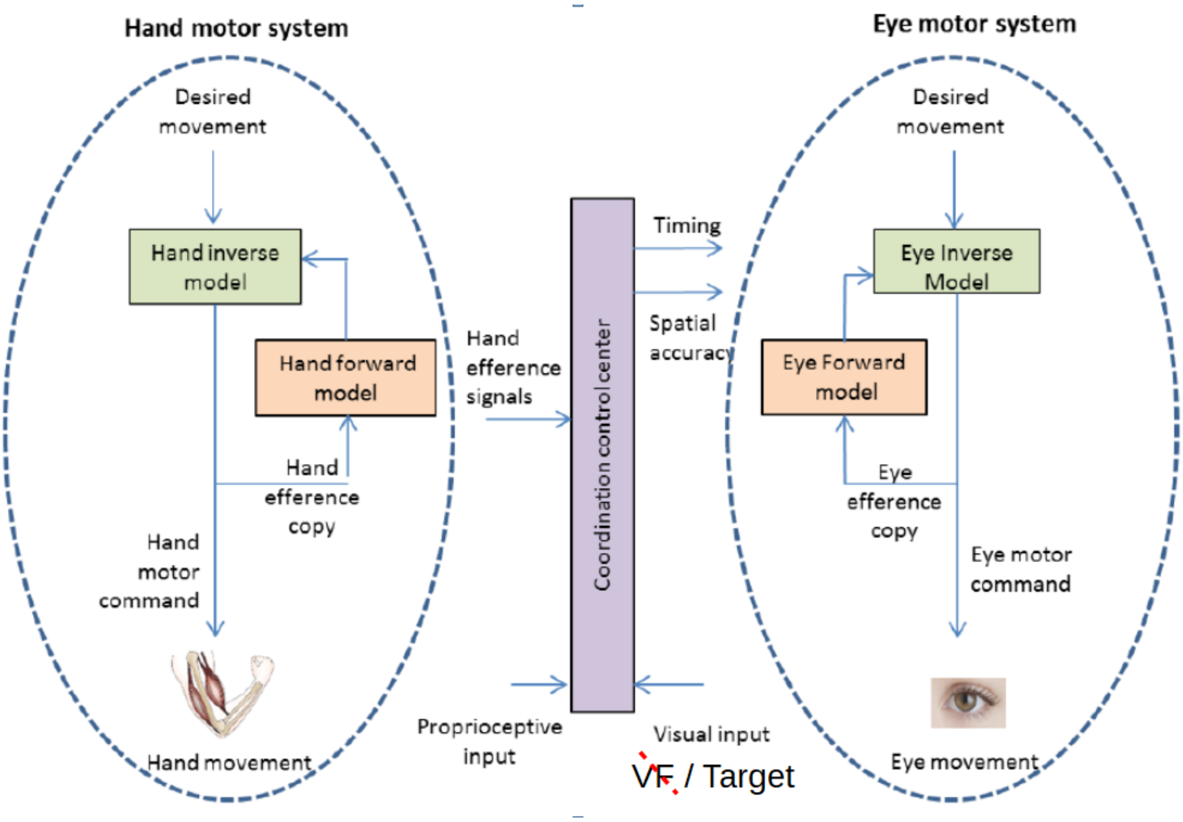

Figure 85: The theoretical model proposed for the coordination between eye and hand [6] [38]. The typical model for condition with active movements of the hand and the visual feedback (VF). The only change on the model when there is no visual feedback with active movement is the removing of VF (Red line) in the visual input.

7.1 Vision for action: role of the vision in the hand tracking

To study this role of vision, only the visual feedback (VF) is removed of the visual input on the figure 85. It will be observed that this change has not a big impact on the task of following the target with the eyes but the parameters of the hand are impacted.

Is the visual feedback necessary for spatial accuracy in the hand tracking?

No significant difference is observed concerning the position error between the target and the eye so the visual feedback is not necessary for the spatial accuracy of the eye in this task. It is explained by the fact that the goal is to follow the target with the eye and not the visual feedback. However a small not significant increase of the position error is observed when the visual feedback is plotted with curve trajectories because the gaze is disturbed by this one that is not far from the target.

Conversely, the visual feedback is necessary for a better spatial accuracy of the hand. Indeed, it is possible for the subject to see during the trial if is close to the target and adapts his movement to get closer to the target.

Is the visual feedback necessary for the tracking speed accuracy in the hand tracking?

Regarding the smooth pursuit velocity error of the eyes, the presence or the absence of visual feedback seems to have no effect on this. Again, this can be explained by the fact that the goal is to follow the target, not the visual feedback.

For the hand, there is a significant increase of the velocity error when the visual feedback is not plotted with no predictable (curve) trajectories. Indeed, the participant does not know the exact position of his hand and therefore he makes smaller or bigger movements which implies different speeds. It is not the case with trajectories more predictable as straight line paths where no significant difference is noticed.

Is the visual feedback necessary for the temporal accuracy in the hand tracking?

Even if it is not statistically significant for the condition with straight line movements, the lag of the eye seems to be smaller without visual feedback for the two kinds of trajectories. One more time, this observation can be explained with the fact that when the visual feedback is plotted, the gaze is between the target and the visual feedback. The gaze is disturbed by the visual feedback when the goal is to follow the target with the eyes.

Concerning the effect of the visual feedback on the lag between the target and the hand, no evidence of an impact could be established.

7.2 Action for vision: the role of proprioception in the eye tracking

The internal model for the conditions with passive movements of the hand is presented in the figure 86. The movement of the hand is not voluntary so the hand motor system of the previous internal model is removed. Thus in this case, there is no efferent signal of the hand (remove of the red crosses on the figure 86) so there is only the presence of afferent signals of proprioception (proprioceptive input). Moreover, when the visual feedback of the hand (target) is not plotted, it is also necessary to remove the visual input (orange cross) of the internal model.

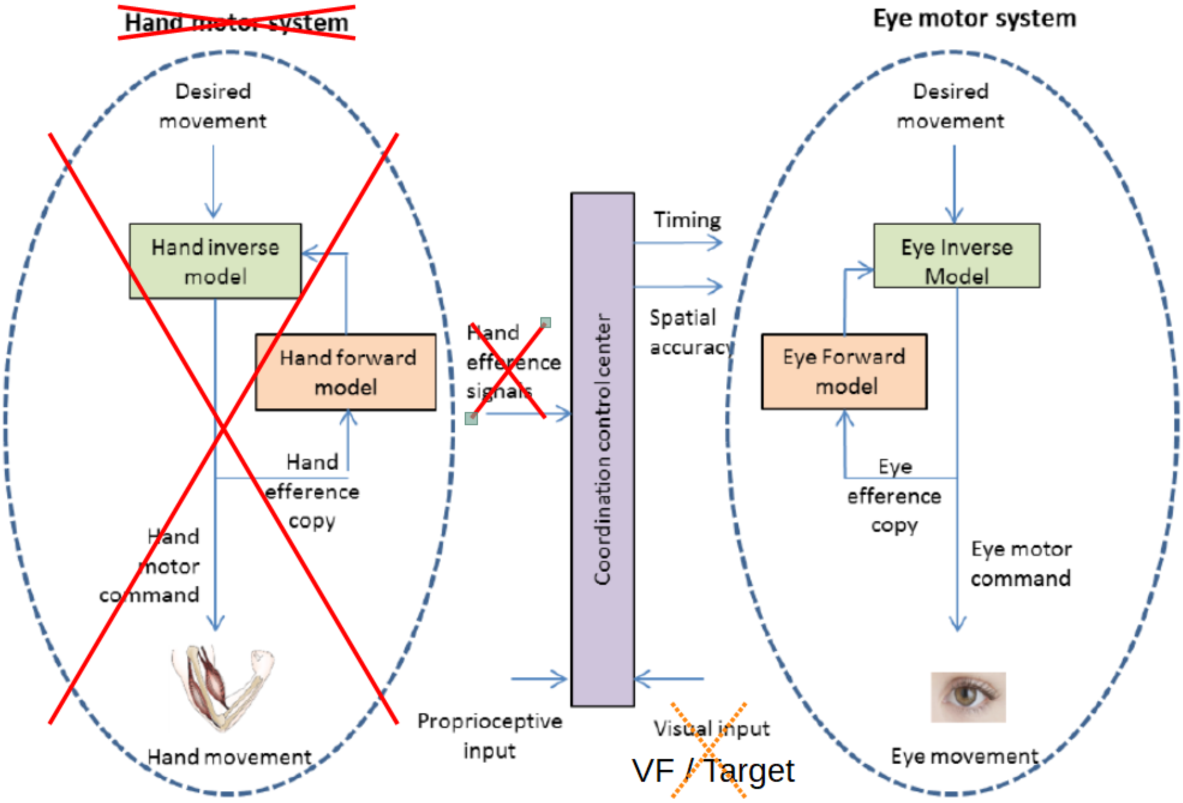

Figure 86: The theoretical model proposed for passive conditions [6] [38]. In red, all parts of the general model removed for passive movements with the visual feedback. When the visual feedback (the target) is not plotted, it is also necessary to remove the visual input (orange part) of the model.

Is the visual feedback necessary for the spatial accuracy in the eye tracking?

It is observed in both kinds of trajectories that the visual feedback increases the spatial accuracy. Indeed, when the participant has only the proprioception sensors to know the position of the hand, the position error between the eye and the target increases significantly.

Does the visual feedback have an influence on the tracking speed in the eye tracking?

When the visual feedback is absent, the gaze makes a lot of large saccades to follow the hand. During curve trajectories, this gaze strategy impacts the smooth pursuit velocity error with significant bigger values than when the visual feedback is plotted. Indeed the eye movements are linear between these saccades. However the predictability of straight line movements ensures that the smooth pursuit velocity error is not impacted by the absence of the visual feedback.

Does the visual and proprioceptive feedback have an influence on the temporal accuracy of the eye?

The lag of the eyes with passive movements and the visual feedback is close to zero that means that the addition of the proprioceptive input on the target improves the temporal accuracy of the eyes. Then when the visual feedback disappears, the lag of the eye becomes negative that means the participant attempts to predict the trajectory of the hand.

7.3 Role of the hand proprioception

The model for conditions with only eye tracking and hand at rest is resumed by the forward and inverse models for the eye motor system (Figure 87).

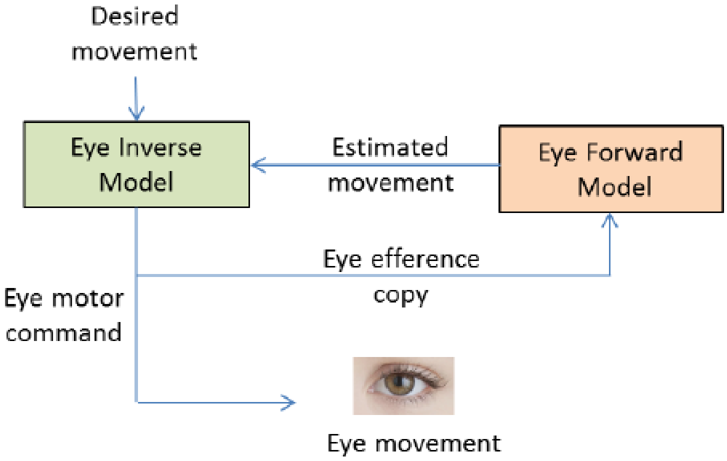

Figure 87: The theoretical model proposed for only eye tracking with hand at rest [6].

The comparison of these conditions where there is only the eyes tracking with conditions accompanied by passive or active movements of the hand does not contribute anything concerning the spatial accuracy. The next question is more interesting.

What is the predictive component in the eye for tracking? Is there any alteration in that during other conditions?

The temporal accuracy of the condition with only eye and curve trajectories (no predictable trajectories) is close to conditions with active movements that means that the second task with active movements of the hand does not alter the lag. Then the lag is reduced thanks to the help of the proprioceptive input of the passive conditions. This proves that the proprioceptive input plays a role of prediction when the trajectory is not predictable.

However, when the trajectory is predictable, it is observed that the second task of active movements damages the temporal accuracy. Then the inclusion of the proprioceptive input on the target with passive movements does not improve the temporal accuracy compare to the condition with only eye tracking.

7.4 Role of the efferent proprioceptive signals in the eye tracking

The question is to know if there is any difference in the eye tracking in active (with the presence of afferent + efferent proprioceptive signals) and passive (with the presence of afferent only) hand motion? If the answer is positive, in which parameter? In spacial accuracy? In temporal accuracy?

Does the hand efferent signals improve the spatial accuracy of the eye?

When the visual inputs are plotted and more particularly the target, it is observed that the spatial accuracy only depends on this last one. Indeed there is not any difference of position error between conditions with active movements and the condition with passive movements of the hand and with target plotted. So the hand efferent signals do not seem to play a role on the spatial accuracy of the eye.

Does the hand efferent signals improve the tracking speed of the eye?

One more time, the tasks with active movements of the hand and the condition with the passive movement (with target plotted) are very similar and consists of following a target with the eyes. Thus, no difference is observed between these conditions and so the hand efferent signals do not improve the smooth pursuit velocity error.

Does the hand efferent signals improve the temporal accuracy of the eye?

The hand efferent signals present in active movements do not improve the temporal accuracy of the eye. Conversely, it is observed that when the afferent signals are in the the target (passive movements) with the visual feedback, the temporal accuracy increases and the lag becomes closer to zero.

7.5 Saccades analysis

Whether the proprioceptive feedback is more utilised by saccadic circuits or smooth pursuit circuits?

It is observed that the saccades travel more distance during conditions with passive movements and without the visual feedback. This distance can represent 70 percents of the distance travelled by the eyes when the trajectory is not predictable and the subject has only the proprioceptive sensors to know the position of the hand. In addition, the contribution of the proprioception during passive movements with the visual target is not conducive to smooth pursuit compared to condition with only eye movements and the hand at rest. This way, it is concluded that the proprioceptive input is more used by the saccadic circuit.

Does the hand efferent signals improve the smooth pursuit circuit ?

It is observed that the participant travels less distance with saccades and favour the smooth pursuit circuit thanks to hand efferents signals of the active movements. Indeed, there are less saccades during conditions with active movements of the hand compared to conditions with the hand at rest.

7.6 Role of the predictability of the trajectory

It is interesting to compare the parameters of curve trajectories with straight line paths to see if the predictability of the paths changes them or not.

Does the predictability of the trajectories have an influence on the spatial accuracy of the eye?

No difference is observed between the two kinds of trajectories for the position error with the exception of the conditions with passive movements and without the visual feedback (target). Indeed when the participant has only the afferent hand signals (proprioceptive sensors) to know the position of the target, the position error increases when it is more difficult to predict the trajectory.

Does the predictability of the trajectories have an influence on the tracking speed of the eye?

There are two critical differences in the tracking speed between the two types of paths. Firstly an increase of the smooth pursuit velocity error is noted when the visual feedback (target) disappears with passive movements and curve trajectories. However, this increase is not observed with predictable paths. Secondly the values of the smooth pursuit velocity error seem to be bigger with no predictable paths but this observation should be carefully taken because this can be partly explained by the difference of velocity range between the two kinds of trajectories.

Does the predictability of the trajectories have an influence on the temporal accuracy of the eye?

Except for the conditions with passive movements and with the visual feedback (E and H), the predictability of the trajectories influence the temporal accuracy with different values of lag. Another difference is that the condition with only eye tracking and hand at rest is close to active conditions with curve trajectories and close to passive conditions with straight line paths.

Does the predictability of the trajectories have an influence on the saccadic circuit?

The predictability of the trajectories influences all the parameters of the saccadic circuit as the amplitude, the rate and the percent of saccades distance. Indeed, the values of parameters are bigger for all conditions with curve trajectories.

7.7 Reaction Time

Only conclusions for the reaction time of the eye with curve trajectories are done. So, it is observed that the reaction time of the eye decreases when the visual feedback is not plotted during active tasks. This can be explained by the fact that the participant used the disappearance of the target as starting stimulus besides the starting movement of the target. This reaction time is even shorter when it is not necessary to do the second task of following the target with the hand (hand at rest). Thus the participant is more concentrated on only one task. Lastly the shortest reaction time (latency of a normal saccade) is observed when the proprioceptive sensors are added on the visual target. Finally, the reaction time increases in the last condition when there are only the proprioceptive sensors as stimulus but this one is similar to the condition with active movements.

7.8 Role of the directions

Does the direction of the target with straight line movements have an influence on the position error of the eyes and the hand?

Even tough the position error of the eye for the downward course to the right seems to be smaller, the difference is not statistical significant. Concerning the position error of the hand, no difference is observed depending on the direction.

Does the direction of the target have an influence on the temporal accuracy?

In both kinds of trajectories, it is observed that directions in upper-left quadrant of the vision are more lagging. On the other hand, the directions in the lower-right quadrant of the vision have the finest temporal accuracy. Two assumptions are made for these observations. First, it is because the robot takes the measure of the gaze only in the dominant eye (all participants have the dominant right eye) and that is more difficult for the right eye to follow a target in the upper left. The second hypothesis is that the eye tracker is less accurate for these trajectories. According the article of R.J Beers and al. [58] : *Visual localization is more precise in the azimuthal direction with regard to the cyclopean eye than in the radial direction* [9]*. This is at least partly a result from the subjects looking down on the horizontal plane.*

7.9 Further testing conducted

Does the hand used have an influence on the parameters?

In this section, it proves that the hand used does not impacts the behaviour of the eyes trajectories. Indeed, this observation corresponds in the search of the state of the art [33].

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[9] The azimuthal direction represents a lateral movement of the pupil in opposition of the pupil's elevation [59].

Is the 2D lag is more impacted by the lag on x-axis or y-axis ?

It is observed that the 2D lag is significantly more impacted by the lag on the y-axis in conditions with active movements or with only eye movements.

Does the lag is the true lag?

It is proved that the lag is true for conditions with active movements and conditions with the only eye because the position error significantly decreases with the lag compensated. Conversely, the non-ejection of the null hypothesis on equality between conditions with or without lag compensated of passive movements proves nothing because the lag is close to zero so the lag compensated does not change the position error.

7.10 Reliability of the data

Do the participants represent a reliable sample of the population?

13 participants were used for the analysis which is sufficient for statistical analysis. However, these people do not represent a reliable sample of the world population. Firstly because the subjects are between the ages of 18 and 32, they are all right-handed and are students. Moreover, the subjects went on 2 or 3 different days and it is observed that the data quality varies from day to day. Indeed, some parameters such as the session time, the tiredness and the stress could be biasing factors. For example, one subject was very tired for the last session and another one had a cold.

Are the data collected reliable?

Concerning the reliability of the target and hand signals, the accuracy of the sensors in the handles are at the cutting edge of technology. For the eye data, even if the data are processed before analysing, the reliability is not complete. Indeed, the head moves, and the eyes get tired during session. In addition, calibration of the eye is complicated for some subjects because it can depend on the position of the participant, the shape and the colour of the eyes. Subjects need to be regularly reminded not to squint the eye too much, to do not to blink too much and to keep eyes wide open during the trial.

7.11 Area of improvements

It is a project completed over one year. Indeed, it should be possible to realise more analysis and a suggestion would be to analyse more the dynamic movements of the hand as well as the saccades of the eyes. A further analysis would be to study how the visual feedback or the proprioception feedback affect the frequency of the error correction. For this end, a FFT (Fast Fourier Transform) analysis might be useful to understand visuo-feedback loops and proprio-feedback loops. Regarding the impact of the hand used, only the analyses of the eyes were done and as expected no difference was found [6] but with the data it is also possible to analyse the consequences on the hand motions. In addition, more analyses can be performed with the data from the curved trajectories separated according to directions. The learning process is not studied in this thesis because it has been shown that there was none in a similar protocol for curve trajectories [5] but it might be necessary to prove that this is also the case with straight line movements.

If the protocol has to be perform once again, the straight line movements or the predictable paths would have been modified to get closer kinematics of the curve paths. That is mean not start with zero speed and have a more similar mean of velocity that curve paths. It is also possible to improve the detection of blinks and saccades during the data processing. Indeed, the operator can save analysis time by improving the Matlab program. Then, the robot allows only movements on a horizontal plane, maybe in the future, the protocol could be adapted with movements on a vertical plane or on a 3 dimensions environment.

Finally, the participant's comfort could be improved with a good height-adjustable chair, a better resting bracket for the head and if we figured out a way to avoid keeping people's head still for an hour.

8 Conclusions

In conclusion, a theoretical model for the coordination between eyes and hands is suggested to explain the visuo-haptic matching in tracking tasks. To understand its various components, a protocol was used to collect valid data on thirteen volunteers. This way, fourteen different conditions of tracking tasks are used to isolate parts of the model.

Firstly, it is observed that the presence of the visual feedback of the active movement of the hand has not a big effect on the task of following the target with the eyes but increases the accuracy of the hand movement. When the afferent signal of the hand becomes the target (passive movements), the spatial accuracy of the eye increases with the visual feedback and the temporal accuracy is closed to zero. A predictive model is observed when the participant has only the afferent signal of the hand (proprioception sensors) as information. It is proved that the proprioceptive input is more used by the saccadic circuit. Conversely, the smooth pursuit circuit is improved by the efferent signal of the hand. It is noted that several parameters of the accuracy or of the saccadic circuit depend on the predictability of the trajectory. The conditions with curve trajectories have an influence on the reaction time of the eyes. Finally it is observed that the temporal accuracy decreases for targets in upper-left quadrant of the vision.

To conclude, this thesis does not allow to obtain a internal model that perfectly fits the reality but it confirms some observations described in the scientific literature and raises new opportunities of experimental designs.

References

[1] J. D. Crawford, W. P. Medendorp, and J. J. Marotta. Spatial transformations for eye–hand coordination. *Journal of Neurophysiology*, 92(1):10–19, 2004. doi: 10.1152/jn.00117.2004. URL `https://doi.org/10.1152/jn.00117.2004`. PMID: 15212434.

[2] Irene A. Kuling, Willem J. de Bruijne, Kimberley Burgering, Eli Brenner, and Jeroen B. J. Smeets. Visuo-proprioceptive matching errors are consistent with biases in distance judgments. *Journal of Motor Behavior*, 51(5):572–579, 2019. doi: 10.1080/00222895.2018.1528435. URL `https://doi.org/10.1080/00222895.2018.1528435`. PMID: 30375949.

[3] Anirban Dutta, Uttama Lahiri, Abhijit Das, Michael A. Nitsche, and David Guiraud. Post-stroke balance rehabilitation under multi-level electrotherapy: a conceptual review. *Frontiers in Neuroscience*, 8:403, 2014. ISSN 1662-453X. doi: 10.3389/fnins.2014.00403. URL `https://www.frontiersin.org/article/10.3389/fnins.2014.00403`.

[4] S. Micera B. B. Edin L. Beccai C. Cipriani M. C. Carrozza, G. Cappiello. Design of a cybernetic hand for perception and action. *Biological Cybernetics*, 95:629, 2006.

[5] L. Martin Y Muyshondt and E. Vansnick. Studying dynamic tracking by the hand and the eyes. *Ecople Polytechnique de Louvain*, 2019.

[6] J. Mathew. Investigating predictive mechanisms underlying eye-hand coordination. *These de doctoral de l'université d'Aix-Marseille*, 2018.

[7] B. Roberfroid A-S Verstraete L. Leyssens, J. Lhoir. The intraocular lens. *LGBIO2220 : Seminar and project in biomedical engineering: Scientific and industrial challenges (UCL)*, 2017.

[8] Pro visu. Oeil et vision, anatomie de l'oeil. `https://www.provisu.ch/fr/dossiers/oeil-et-vision.html`.

[9] P. Lefèvre. Organes artificiels et réhabilitation. *LGBIO1114 (EPL)*, 2016.

[10] P. Lefèvre. Modelling of biological systems. *LGBIO2060 (EPL)*, 2016.

[11] Dinda Nitami. Optical instrument (eyes part). `http://queenitami.blogspot.be/2012/04/optical-isntrument-eyes-part.html`.

[12] O. Jones. The extraocular muscles (teachme anatomy). https://teachmeanatomy.info/head/organs/eye/extraocular-muscles/, 2020.

[13] T. Foulsham. Eye movements and their functions in everyday tasks. *Eye : The scientific Journal of the Royal College of Ophtalmologists*, 29(2):196–199, 2015.

[14] Christian Quaia, Philippe Lefèvre, and Lance M. Optican. Model of the control of saccades by superior colliculus and cerebellum. *Journal of Neurophysiology*, 82(2):999–1018, 1999. doi: 10.1152/jn.1999.82.2.999. URL `https://doi.org/10.1152/jn.1999.82.2.999`. PMID: 10444693.

[15] Jean-Jacques Orban de Xivry and Philippe Lefèvre. Saccades and pursuit: two outcomes of a single sensorimotor process. *The Journal of Physiology*, 584(1):11–23, 2007. doi: 10.1113/jphysiol.2007.139881. URL `https://physoc.onlinelibrary.wiley.com/doi/abs/10.1113/jphysiol.2007.139881`.

[16] Sophie de Brouwer, Marcus Missal, Graham Barnes, and Philippe Lefèvre. Quantitative analysis of catch-up saccades during sustained pursuit. *Journal of Neurophysiology*, 87(4):1772–1780, 2002. doi: 10.1152/jn.00621.2001. URL `https://doi.org/10.1152/jn.00621.2001`. PMID: 11929898.

[17] C.Weber J. Triesch S. Saeb. A neurol model for the adaptive control of saccadic eye movement. *Internation Joint Conference on Neural Networks (IJCNN), FIAS Frankfurt Institute for Advanced Studies*, pages 1–23, 2009. URL `https://slideplayer.com/slide/8597961/`.

[18] J. D. Enderle and J. W. Wolfe. Time-optimal control of saccadic eye movements. *IEEE Transactions on Biomedical Engineering*, BME-34(1):43–55, 1987. doi: 10.1109/TBME.1987.326014.

[19] Knox PC. The parameters of eye movement. `https://www.liverpool.ac.uk/~pcknox/teaching/Eymovs/params.html`, 2018.

[20] C.J. Erkelens. Coordination of smooth pursuit and saccades. *Vision Research, ELSEVIER*, 46(1-2):163–170, 2006.

[21] B. Fischer and R. Boch. Saccadic eye movements after extremely short reaction times in the monkey. *Brain Research*, 260(1):21 – 26, 1983. ISSN 0006-8993. doi: https://doi.org/10.1016/0006-8993(83)90760-6. URL `http://www.sciencedirect.com/science/article/pii/0006899383907606`.

[22] B. Fischer and R. Boch. Hand movement. *Encyclopedia of the Human Brain, Elseiver Science*, pages 399 – 414, 2002. ISSN 0006-8993.

[23] F. R. Sarlegna P. K. Mutha. The influence of visual target information on the online control of movements. *Vision Research, Elsevevier*, 110(B):144–154, 2015.

[24] F. R. Sarlegna R. L. Sainburg. The roles of vision and proprioception in the planning of reaching movements. *Progress in Motor Control. Advances in Experimental Medicine and Biology*, 629:317–335, 2009. doi: 10.1007/978-0-387-77064-2_16. URL `https://doi.org/10.1007/978-0-387-77064-2_16`.

[25] Fabrice R. Sarlegna, Gabriel Baud-Bovy, and Frédéric Danion. Delayed visual feedback affects both manual tracking and grip force control when transporting a handheld object. *Journal of Neurophysiology*, 104(2):641–653, 2010. doi: 10.1152/jn.00174.2010. URL `https://doi.org/10.1152/jn.00174.2010`. PMID: 20538774.

[26] R. Goodman L. Tremblay. Using proprioception to control ongoing actions: dominance of vision or altered proprioceptive weighing? *Experimental Brain Research volume*, 236:1897–1910, 2018.

[27] Y. Rossetti, M. Desmurget, and C. Prablanc. Vectorial coding of movement: vision, proprioception, or both? *Journal of Neurophysiology*, 74(1):457–463, 1995. doi: 10.1152/jn.1995.74.1.457. URL `https://doi.org/10.1152/jn.1995.74.1.457`. PMID: 7472347.

[28] Sarlegna F.R. Sainburg R.L. Bagesteiro, L.B. Differential influence of vision and proprioception on control of movement distance. *Exp Brain Res*, 171:358–370, 2006. doi: 10.1007/s00221-005-0272-y. URL `https://doi.org/10.1007/s00221-005-0272-y`.

[29] A. Polit and E. Bizzi. Characteristics of motor programs underlying arm movements in monkeys. *Journal of Neurophysiology*, 42(1):183–194, 1979. doi: 10.1152/jn.1979.42.1.183. URL `https://doi.org/10.1152/jn.1979.42.1.183`. PMID: 107279.

[30] J. Gordon, M. F. Ghilardi, and C. Ghez. Impairments of reaching movements in patients without proprioception. i. spatial errors. *Journal of Neurophysiology*, 73(1): 347–360, 1995. doi: 10.1152/jn.1995.73.1.347. URL `https://doi.org/10.1152/jn.1995.73.1.347`. PMID: 7714577.

[31] Fabrice Sarlegna. La main vers la cible : intégration multi-sensorielle et contrôle en ligne du mouvement de pointage. 2007. ISSN 0003-5033. URL `https://www.persee.fr/doc/psy_0003-5033_2007_num_107_2_30998`.

[32] Amouroux V. Mizrahi L. Notre véritable 6e sens. *ARTE France Mona Lisa Production Fauns*, 2019. URL `https://www.arte.tv/fr/videos/073879-000-A/notre-veritable-6e-sens/`.

[33] Laura Mikula, Valérie Gaveau, Laure Pisella, Aarlenne Z. Khan, and Gunnar Blohm. Learned rather than online relative weighting of visual-proprioceptive sensory cues. *Journal of Neurophysiology*, 119(5):1981–1992, 2018. doi: 10.1152/jn.00338.2017. URL `https://doi.org/10.1152/jn.00338.2017`. PMID: 29465322.

[34] Smeets JB Kuling IA, Brenner E. Proprioception is robust under external forces. *PLoS One*, 8(9), 2013. doi: 10.1371/journal.pone.0074236. PMID: 24019959.

[35] R. L. Sainburg, M. F. Ghilardi, H. Poizner, and C. Ghez. Control of limb dynamics in normal subjects and patients without proprioception. *Journal of Neurophysiology*, 73 (2):820–835, 1995. doi: 10.1152/jn.1995.73.2.820. URL `https://doi.org/10.1152/jn.1995.73.2.820`. PMID: 7760137.

[36] J. Paillard and D. Beaubaton. De la coordination visuo-motrice à l'organisation de la saisie manuelle. *Du contrôle de la motricité à l'organisation du geste. Paris, Masson.*, pages 225–260, 1978.

[37] J. R. Lackner. Adaptation to visual and proprioceptive rearrangement: Origin of the differential effectiveness of active and passive movements. *Perception Psychophysics*, 21(1):50–59, 1977.

[38] S. Lazzari, J. L. Vercher, and A. Buizza. Manuo-ocular coordination in target tracking. i. a model simulating human performance. *Biological cybernetics*, 77(4):257–266, 1997. ISSN 0340-1200. URL `http://dx.doi.org/`.

[39] Martin J. Steinbach and Richard Held. Eye tracking of observer-generated target movements. *Science*, 161(3837):187–188, 1968. ISSN 0036-8075. doi: 10.1126/science.161.3837.187. URL `https://science.sciencemag.org/content/161/3837/187`.

[40] P.W. Koken C.J. Erkelens. Influences of hand movements on eye movements in tracking tasks in man. *Experimental Brain Research*, 88:657–664, 1992.

[41] C. Ghez, J. Gordon, and M. F. Ghilardi. Impairments of reaching movements in patients without proprioception. ii. effects of visual information on accuracy. *Journal of Neurophysiology*, 73(1):361–372, 1995. doi: 10.1152/jn.1995.73.1.361. URL `https://doi.org/10.1152/jn.1995.73.1.361`. PMID: 7714578.

[42] L. Ren J.D. Crawford. Coordinate transformations for hand-guided saccades. *Experimental Brain Research*, 195:455–465, 2009.

[43] D. Y. P. Henriques J.D. XCrawford. Direction-dependent distortions of retinocentric space in the visuomotor transformation for pointing. *Experimental Brain Research*, 132:179–194, 2000.

[44] D. Pelisson C. Prablanc M. A. Goodale. Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Macmillan Journals Ltd.*, 320(6064):748–750, 1986.

[45] M. j. Steinbach. Eye tracking of self-moved targets: The role of efference. *Journal of Experimental Psychology*, 82(2):366–376, 1969.

[46] G. M. Gauthier J. M. Hofferer. Eye tracking of self-moved targets in the absence of vision. *Experimental Brain Research*, 26:121–139, 1976.

[47] Reza Shadmehr, Maurice A. Smith, and John W. Krakauer. Error correction, sensory prediction, and adaptation in motor control. *Annual Review of Neuroscience*, 33(1):89–108, 2010. doi: 10.1146/annurev-neuro-060909-153135. URL `https://doi.org/10.1146/annurev-neuro-060909-153135`. PMID: 20367317.

[48] N. Gueugneau C. Papaxanthis F. Lebon. Modèles internes et imagerie motrice, internal models and motor imagery. *Mov Sport Sci/Sci Mot*, 82:51–61, 2013.

[49] Kazunori Furukawa R. Suzuki M. Kawato. A hierarchical neural-network model for control and learning of voluntary movement. *Biological Cybernetics*, 57:169–185, 1987.

[50] C.R. Lowrey T. Takey S.H. Scott, t. Cluff. Feedback control during voluntary motor actions. *ScienceDirect, Elsevier*, 33:85–94, 2015.

[51] Gerry Leisman. The brain on art: Auditory, visual, spatial aesthetic, and artistic training facilitates brain plasticity. 2, 06 2012.

[52] C. Bar I. M. Franks P-M Bernier, R. Chua. Updating of an internal model without proprioception: a deafferentation study. *NeuroReport*, 17(13):1421–1425, 2006.

[53] Michael Wood, Jasmine Khan, Kevin Lee, David Maslove, John Muscedere, Miranda Hunt, Stephen Scott, Andrew Day, Jill Jacobson, Ian Ball, Marat Slessarev, Niamh O'Regan, Shane English, Victoria Mccredie, Michaël Chassé, Donald Griesdale,

and J. Gordon Boyd. Assessing the relationship between near-infrared spectroscopy-derived regional cerebral oxygenation and neurological dysfunction in critically ill adults: a prospective observational multicentre protocol, on behalf of the canadian critical care trials group. *BMJ Open*, 9:e029189, 06 2019. doi: 10.1136/bmjopen-2019-029189.

[54] SR Research EyeLink. The eyelink 1000 plus eye tracker ®. 2020. URL `https://www.sr-research.com/wp-content/uploads/2018/01/EyeLink-1000-Plus-Brochure.pdf`.

[55] Iris Mulders. Infant experiments with the arm-mounted babyeyelink. *UIL OTS : Utrecht Institute of Linguistics*, 2020. URL `https://uilots-labs.wp.hum.uu.nl/how-to/infant-experiments-with-the-arm-mounted-eyelink/`.

[56] R.C. Oldfield. Yhe assessment and analysis of handedness. *Neuropsychologia*, 9: 97–113, 1971.

[57] F.R. Danion J.R. Flanagan. Different gaze strategies during eye versus hand tracking of a moving target. *Scientific reports*, 8:10059, 2018.

[58] Robert J. van Beers, Anne C. Sittig, and Jan J. Denier van der Gon. Integration of proprioceptive and visual position-information: An experimentally supported model. *Journal of Neurophysiology*, 81(3):1355–1364, 1999. doi: 10.1152/jn.1999.81.3.1355. URL `https://doi.org/10.1152/jn.1999.81.3.1355`. PMID: 10085361.

[59] Davide Zoccolan, Brett Graham, and David Cox. A self-calibrating, camera-based eye tracker for the recording of rodent eye movements. *Frontiers in neuroscience*, 4: 193, 11 2010. doi: 10.3389/fnins.2010.00193.

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