

How is responsibility assigned in a redundant system during a bimanual task ?

Dissertation presented by
Méric KLEIN , Simon KNEIPE

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Supervisor(s)
Philippe LEFÈVRE, Jean-Louis THONNARD

Reader(s)
David CORDOVA BULENS, Yannick BLEYENHEUFT

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Abstract

Redundancy is a key feature of the motor system of human beings. Indeed, the numerous combinations of motor commands for the different effectors lead to various ways of achieving a desired task. When doing a bimanual task, the motor system will always distribute the work across the different effectors according to what it estimates to be the optimal way to produce the desired movement. But, when it faces an error, the motor system usually does not know which effector caused it. The aim of our study is to investigate the way our motor system assigns responsibility when it faces an error induced by a hidden visuomotor rotation during a bimanual task. To do so, we induced progressively the visuomotor rotation until reaching an amplitude of 30 degree and then, we anchored the visuomotor rotation at this amplitude. Our results show that the responsibility is assigned across the effectors according to biomechanical constraints. The force production is always driven by the preferential direction of the hand, meaning that the hand produces more force when the target to reach is close to its preferential direction. Moreover, corrections in the trajectory are mostly achieved by the other hand, so the one for who the target is not located close to its preferential direction of force production. Eventually, our results also show that handedness does not impact the force production or the correction of the visuomotor rotation.

CONTENTS

1	Introduction	1
1.1	General introduction	1
1.2	Motor prediction	2
1.3	Bimanual movements	3
1.4	Influence of biomechanics	5
1.5	Aim of the work	7
2	Methods	9
2.1	Materials	9
2.2	Subjects	11
2.3	Experiment	11
3	The Programming Environment	17
3.1	Custom Task Program	17
3.2	Mathworks' Simulink	17
3.3	Stateflow chart	20
3.4	BKIN Dexterit-E	23
4	Results	27
4.1	Validation of the experimental task	27
4.2	Left visuomotor rotation	29
4.3	Right visuomotor rotation	33
4.4	Evolution of the forces trajectory	37
4.5	Evolution of the cursor trajectory with the progressive visuomotor rotation . . .	40
5	Discussion	43
5.1	Adaptation to the visuomotor rotation	43
5.2	Influence of the direction of the visuomotor rotation	44
5.3	Amplitude of the correction	45
5.4	How is responsibility assigned in a redundant system during a bimanual task ? .	46
6	Conclusion	49
	Appendices	53
A	Edinburgh Handedness Inventory	54

B	Parameter Table Defn	56
C	Edit Task Protocol into Dexterit-E	57
D	Success rate	59
E	Force Production Map for cursor jumps of 0cm	60
F	Amplitude of the angle in the forces trajectory	61
G	Amplitude of the angle in the forces trajectory for the cursor jumps	62
H	Evolution of the cursor trajectory	64

CHAPTER 1

INTRODUCTION

1.1 General introduction

Human being. Everybody knows what those words mean. Everybody knows that human beings are made of tissues and organs, that they have to breathe oxygen, eat food and drink water if they want to survive. Everybody knows that, in general, a human being has two arms, two legs, one head with two eyes, a nose, a mouth and two ears. Everybody knows it, because human being are familiar words to all of us. Familiar maybe, but yet so poorly understood...

For decades now, human beings are studying themselves in order to understand how they work, how they react to unexpected situations, how they adapt into different environments, ... One of the purpose of all this is, of course, to improve our medicine, treatments and rehabilitation procedures. But all these studies are so hard, so complex and so time-consuming that even now, many things remain unexplored and/or not understood.

The planning and production of movement is one of them. And even if, for humans, this task is natural, it remains very complex. Besides, many different disciplines have found interest studying the motor control, notably cognitive science, biomechanics and neuroscience. During this work, we will try to combine them in order to understand how people react to perturbations during motor tasks.

And when we study biological motor systems, redundancy is a fundamental feature. Indeed, the generation of a simple movement derives from the final objective of this movement. Human beings use the motor control of different members and muscles to achieve the goal fixed. As an example, if you want to reach a point in front of you with a finger, the motor command that you will use will be related to this task : elongation of your arm, hand and finger in the right direction to finally bring your finger on top of the point. Said this way, it might seem quite easy. But, there are a really huge number of different feasible combinations of postures that will place your finger at the same point in space [1]. So, exploiting this redundancy, it has been shown that the adopted posture depends on many different parameters, like the initial position of the hand and finger, minimizing the amount of work required to move the hand to the planned position, feedback control, adaptation, ... [2, 3] Fundamentally, humans determine the optimal movement to produce in order to achieve their task thanks to all the information at their disposal. This goes from the surrounding environment (presence of water that will slow down the movement, walking on sand or concrete, ...) to the current state of their body [4, 5]. An example can be seen on figure 1.1, where situation B will be preferred compared to situation A because, as human beings, we judge this second possibility better than the first one, due to its lower cost.

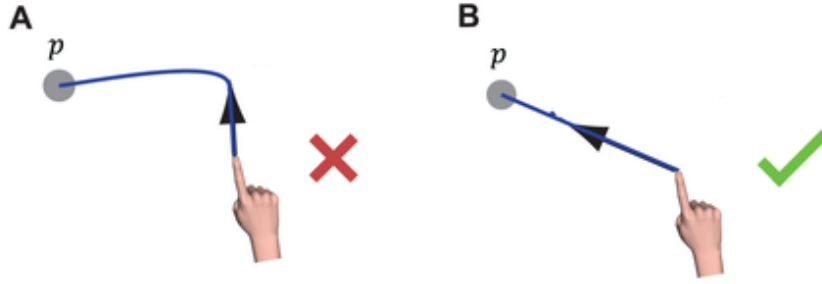


Figure 1.1: Example of two possible movements to reach the same target. Situation B will be preferred due to its lower cost [6]

1.2 Motor prediction

In order to have an accurate motor control, it is fundamental to know the actual state of our body. This can be obtained thanks to sensory signals. Unfortunately, these signals are corrupted by noise, and also subject to delay due to receptor transduction, neural conduction and central processing. So, especially for fast movements, the use of these sensory signals can lead to errors, which can then lead to instability in the motor control.

An alternative way to predict the state of the body is thus needed. And in order to predict the consequences of a motor command while taking into account the interactions between our body and tools we interact with, this alternative way requires a system that can simulate the dynamic behavior of those tools and our body. So, for motor control and trajectory planning, we rely on an internal forward model to represent neuronal processes used to compare motor commands and estimate their consequences [7, 8, 9, 10].

Practically, we use two different internal models that interact together in order to control the motor system :

- The Inverse Model, that can estimate motor commands based on the desired kinematics
- The Forward Model, that can estimate the predicted kinematics based on efference copies of the motor command

This is represented on figure 1.2.

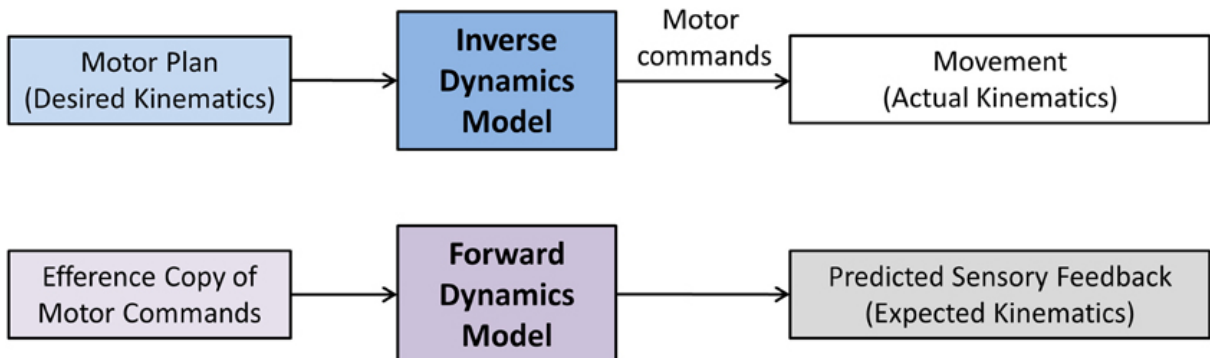


Figure 1.2: Representation of our internal model used for motor control [11]

In this model, a motor plan specifies the desired kinematics of the movement. An inverse dynamics model transforms these planned kinematics into motor commands, which will then result in the appropriate generation of forces that will move the body system in the desired way.

Moreover, an efference copy of the motor commands is used to predict the movement outcome, thanks to a forward dynamics model that performs the reverse operation [11].

The main advantage of this model is that the estimation is made ahead of the movement. The problem of time delay is then solved, but the estimation will drift over time if the forward model is not perfectly accurate. So, to compensate for this drawback, this motor prediction is combined with sensory feedback. This way, our motor control can remain efficient for every kind of movement [7, 8].

Yet, when humans have to repeat the same task over and over again, the same movement is rarely reproducible in the exact same way, even if the task goal remains the same. This proves that noise is well present in motor control. So, in such cases, we rely a lot more on the feedback that makes us correct different aspects of the previous movement that were not adapted or optimal [12].

Finally, it is important to know that forward models are not permanent and invariant things. Indeed, as the dynamics of our body change with our experiments and as we experience tools which have their own intrinsic dynamics, we have to keep our models accurate. Forward models can then be modified through experiments and environment, updated and improved through learning [8].

1.3 Bimanual movements

Everything that has been said until now is applicable to unimanual movements. However, in every day life, we use most of the time our both hands together. Bimanual movements are present everywhere, like for example when we eat (holding our knife and fork), drive our car, type on a keyboard or even just tie our shoes (see figure 1.3).

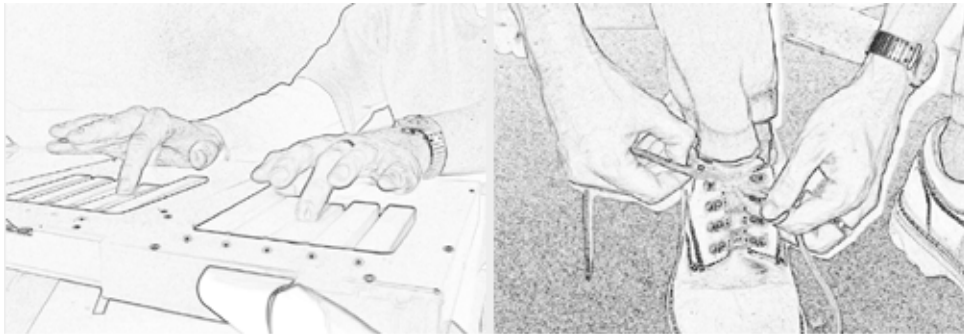


Figure 1.3: Example of every day life bimanual tasks [13]

In order to properly achieve bimanual movements, we have to coordinate our two arms and hands. Once again, this is really complex, even if it seems effortless and automatic to us. When the task is unperturbed in a familiar environment into which we are used to perform different kind of movements, like for example in the street with negligible effect of the wind or in a swimming pool, the motor system distributes work across different effectors in order to realize the task through what it estimates to be the optimal movement, as said before. But, when an error occurs in a redundant movement, the motor system faces a problem. Indeed, it is well possible that it ignores where the error comes from, which effector caused it. Nevertheless, it still has to correct this error. And to do so, an important factor is the handedness. Generally, people have a preferred hand, called dominant hand, that they use more than the other one. Due to this difference, this dominant hand is more used to action and perturbations, and is thus more experienced than the other hand, called the non-dominant hand.

So, in such a case, the motor system has to choose between two different possibilities :

1. It could let the more experienced hand (dominant hand) determine and repair the error, which would be an efficient way to solve this situation
2. It could let the less experienced hand (non-dominant hand) correct and learn from that error, because this hand is more likely the one that caused the error

This shows the importance of responsibility assignment for the two different processes that are online correction (which effector should correct during the current movement) and offline correction (which effector should learn from the error and change its motor command for the next trial).

These two kinds of correction are not related to the same things during visually guided movements that are perturbed. Indeed, while online correction relies on sensory feedback control and takes place immediately after the perturbation (<150 ms), offline correction is made by adjusting the motor planning for the next movement (motor adaptation) [14].

However, motor planning and feedback control are both closely related to each other. It has notably been shown that the planning of movements is supported by highly distributed cortical and subcortical circuits. And recent studies have been able to highlight that goal-oriented feedback used when we make online corrections to counter small disturbances of the limb or altered visual feedback is likely generated by the same neural circuits [15]. Moreover, both of them also use the same visuomotor map that translates the relationship between the direction of the target and the direction of the hand movement. In ordinary situations, these two directions are almost identical, as it can be seen on figure 1.4 A. But this also means that, if this visuomotor map gets modified, as well online as offline corrections will be affected the same way, since they rely on this map for their corrections [14].

So, using this idea, it has been demonstrated that distorting the visuomotor map by applying visual rotations to a cursor representing the hand position, as shown in figure 1.4 B, has a similar effect on the magnitude of online and offline corrections. This is illustrated in figure 1.4 C and D [14].

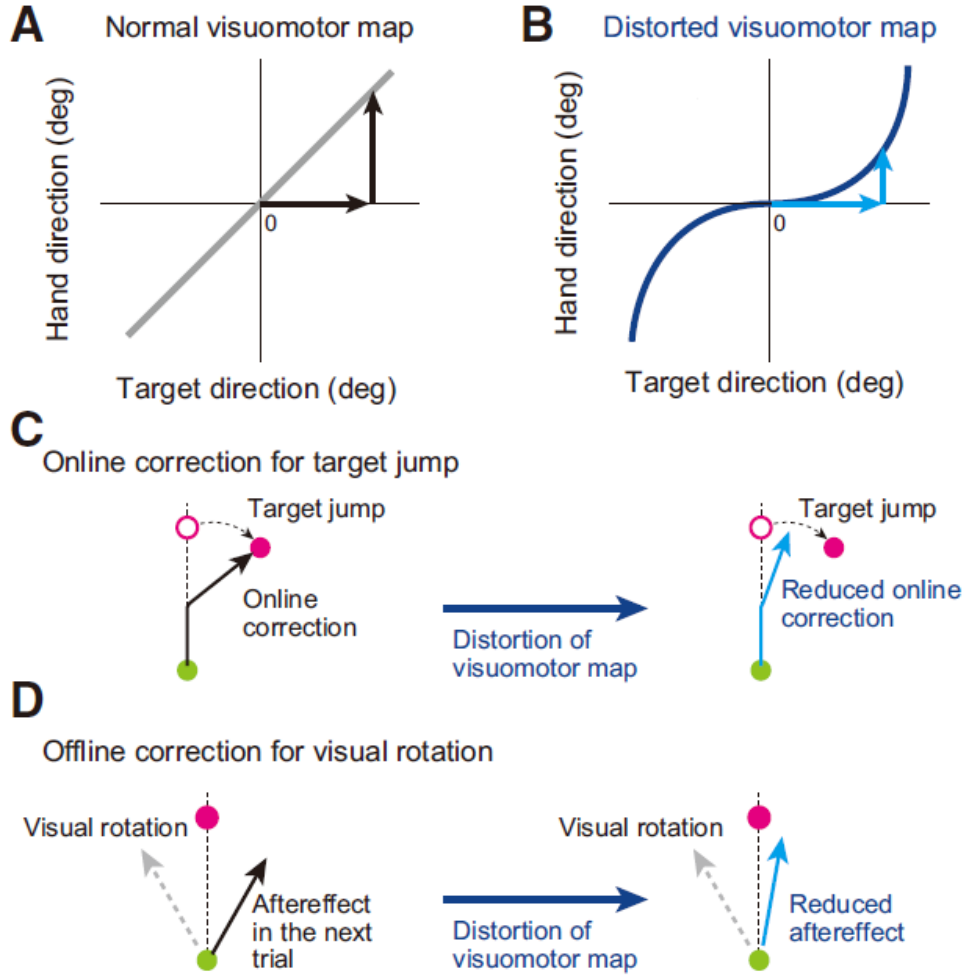


Figure 1.4: Normal visuomotor map (A), distorted visuomotor map (B), online movement correction to a target jump with and without distortion of the visuomotor map (C) and offline movement correction observed after imposing visual rotation with and without distortion of the visuomotor map (D)[14]

Finally, using this idea of a visual rotation of the visuomotor map as a perturbation, White and Diedrichsen (2010) have been able to prove that, for a bimanual redundant task in which a single cursor is presented at the midpoint between the two hands and set in motion thanks to a combined bimanual action, responses to perturbations are applied more on the non-dominant hand. This means that the motor system estimates that the dominant hand is experienced enough to avoid errors, and so that, if an error occurs, it must be due to the non-dominant hand, which is the most likely cause. Then, in order to improve the way we work, it also decides to use this non-dominant hand to correct and learn from the mistake that was made [16].

1.4 Influence of biomechanics

Previous studies have shown that the central nervous system favors the dominant hand during bimanual tasks. Indeed, as stated before, the central nervous system has to deal with redundancy during bimanual tasks. So, control across the two upper-limbs has to be shared, and not specially in a symmetrical way. Besides, handedness is documented as a source of asymmetry [17, 18]. On the other hand, it is also possible that biomechanical considerations have to be taken into account for neural control during bimanual tasks. A recent study has been conducted by David Cordova Bulens to assess whether or not this hypothesis was true. And through a series of

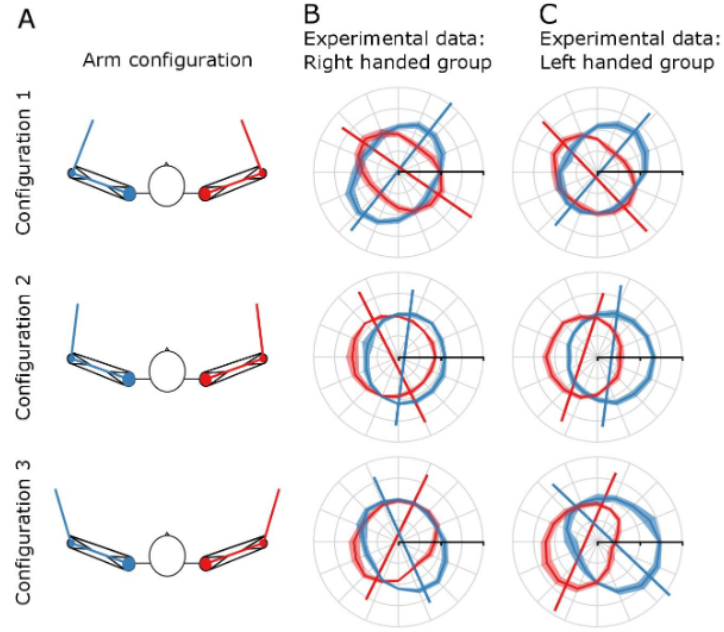


Figure 1.5: Joint configuration (A) and mean experimental results for the right (B) and left (C) handed group [19]

bimanual force production experiments varying the orientation of a target force and the joint configuration used by the subjects to realize the experiment, he has been able to prove that the influence of biomechanical constraints impacted the behavior of both left and right-handed participants similarly. Indeed, he has been able to show that the contribution of each arm was different, depending on the joint configuration as well as the force production direction. This can be seen in figure 1.5, where the results for the three different joint configurations tested during his experimental task are given [19].

Moreover, by introducing perturbations in the task, he has also been able to prove that online corrections of the forces after a sudden change of the end-point during a movement depend a lot on the biomechanical configuration too. Even better, the influence of those corrections was compatible with the force distribution obtained for the unperturbed trials, as showed in figure 1.6.

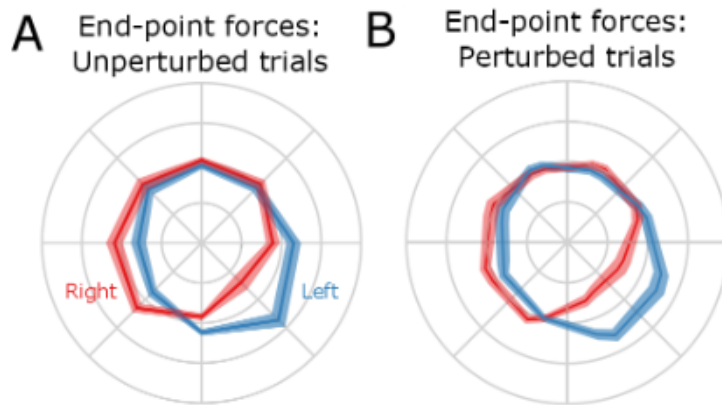


Figure 1.6: Comparison between the forces measured at target reach for all targets and unperturbed trials (A) or perturbed trials (B) [19]

So, these results illustrate that the nervous system during a bimanual task optimally distributes the force generation across limbs for both movement planning and feedback control according to biomechanical constraints [19].

1.5 Aim of the work

As we have seen just above, as well biomechanics as handedness are factors influencing the way motor control is shared across the two upper-limbs during bimanual tasks. But the way they interact together remains unexplored. For now, we ignore if one of these factors is more important than the other one in bimanual movements, and if so, which one is the most important. We ignore if one of them will completely overcome the other one, or if they will be used together by our central nervous system. In fact, we ignore the way responsibility will be assigned when we analyze these two factors at the same time.

So, we decided to focus our work on this problem. More specifically, we will try to answer the question :

"How is responsibility assigned in a redundant system during a bimanual force task ?"

To be able to answer this question, we have to couple both the effects of handedness and biomechanical constraints into a single experiment. And in order to base our work on something known instead of complete unknown, we decided to put together parts of previous works that focus on one single factor. We will then use a bimanual force production task varying the orientation of a target force for a given joint configuration and couple it with the insertion of a rotation of the visuomotor map.

Indeed, by doing that, we can expect to obtain one of the two following results :

- Either we think that we will find results according to handedness, and thus pretty similar to White and Diedrichsen, namely that responses to the visuomotor rotation will be applied more on the non-dominant hand. Indeed, since the visuomotor rotation will be interpreted as an error, our central nervous system might assign this error to the less experienced hand, which is the most likely to have caused it.
- Or it is also possible that we will obtain results according to biomechanics, and thus pretty similar to David Cordova, namely that responses to the visuomotor rotation will be made by both hands according to the direction of the movement, without difference between the dominant and non-dominant hand.

Finally, we also wanted to go a little deeper in the analysis. So, we decided to add a last part on our experiment to see if online perturbations have a significant effect on the assignment of responsibility.

CHAPTER 2

METHODS

2.1 Materials

To be able to answer this question, we will use a bimanual force production task on the robot KINARM. The KINARM End-Point Lab, shown in figure 2.1, is a high performance robot that can create highly complex mechanical environments. Composed of two mechanical arms with a vertical handle at the end of each one of them, this robot is designed for bilateral studies. Indeed, it ensures the simultaneous control of both KINARM End-Point robots, which allows an easy comparison of bimanual performance and coordination.



Figure 2.1: KINARM End-Point Lab Robot [20]

As shown in figure 2.2, subjects are sitting in front of the KINARM, and they are asked to move the two handles. Each hand of the subject has the control of one handle that only moves on the horizontal plane. Subjects can only see a mirror, placed between their head and the handles. This mirror is used to show them the display of our experiment. To ensure that the subject has no vision of his hands, a cover is placed just underneath the mirror, as in figure 2.3.



Figure 2.2: Representation of a KINARM End-Point Lab Robot [21]



Figure 2.3: Example of a subject using a KINARM End-Point Lab Robot [21]

Data acquisition is done at 1kHz. Through a lot of sensors, the robot measures many different parameters : position of the handles, movements made, speed of the movements, forces/torques applied on the handles, their directions, ... The robot KINARM even integrates a gaze-tracking system, but we had no use of it for our research.

The robot KINARM is running with the Dexterit-ETM experimental control software and hardware. In order to code the program of our experimental protocol, we used Matlab, and more specifically the Simulink environment, and a Stateflow toolbox. Finally, a real time computer controls the robot and follows the program that we want, which is of course, in our case, our experimental protocol [21].

2.2 Subjects

20 subjects participated to our experiment : 13 men and 7 women. All of them were healthy, without any mental or physical disorder. They were aged from 18 to 30 years. Moreover, all our subjects were right-handed. This was assessed through the Laterality Quotient given by the Edinburgh Handedness Inventory that can be found in the Appendix A, in which subjects have to attribute different tasks of everyday life to their favored hand in order to find their dominant hand. In this test, scores can vary from -100 (for complete left hand preference) to 100 (for complete right hand preference), with the neutral behavior represented by a score of 0 [22]. Among our 20 subjects, scores varied from 26 to 100, with a mean of 75.5, proving thus that they were all, as required, right-handed.

Our subjects were also separated in 2 different groups. One of them will experiment the visuomotor rotation towards the left, and the other one towards the right. We chose this separation because we think that if the same participant has to experiment both directions of the visuomotor rotation, he will notice something and react consequently, which is not the purpose of our experiment. Finally, they all gave their informed consent before starting the experiment.

2.3 Experiment

Participants are asked to hold the handles of the two robotic arms of the KINARM. Then, a single cursor will be presented at the midpoint between the two hands, and this cursor will be set in motion by the forces applied on the robotic handles. The goal is to generate a 20N force with the two arms. Moreover, those robotic arms will counteract the forces applied by the participant with a very stiff force field ($K = 2000\text{N/m}$, $B = 50\text{Ns/m}$, same one that David Cordova used for his experiment) in order to limit the movement of both the robotic and participant arms to negligible movements. Finally, we also decided to constrain the subjects in the position represented in figure 2.4b by using supports. This corresponds to the joint configuration 1 of David Cordova's paper [19], which is the one with the highest value for the angles θ_1 (23.86 ± 5.94 [°]) and θ_2 (88.53 ± 5.08 [°]) represented in figure 2.4a. Indeed, since all our subjects are right-handed, we chose to use this configuration because, as you can see on figure 1.5B, it is the one that will give us the most different force contribution for each hand according to the direction of the force that has to be produced.

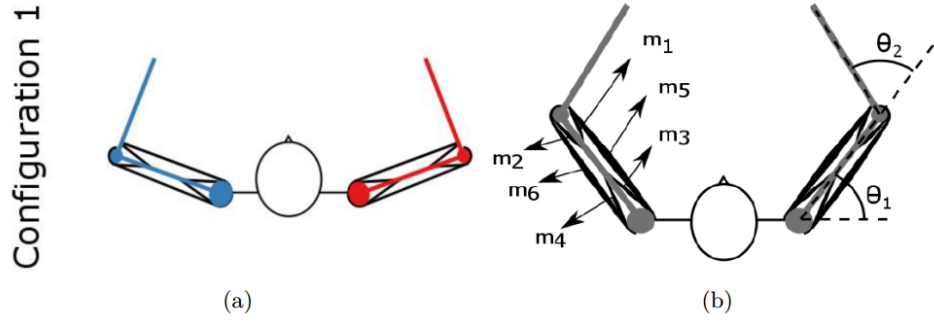


Figure 2.4: Arm configuration chosen for our experiment (a) and Joint configuration model (b) [19]

During the experiment, the cursor controlled by the subject is a red circle (diameter = 0.5cm). To begin a trial, the subject only has to keep the cursor into a "Starting point" (diameter = 1cm, color = white) for 1 second. The center of this Starting point corresponds to the position of the cursor when no force is applied by the subject. So, this condition is simply obtained by relaxing the forces applied on the handles of the robot. That being done, the Starting point will disappear, indicating that the subject has to start the trial. The participant is then asked to reach a target. This target is a new circle that becomes visible when the Starting point disappears (color = purple, diameter = 1cm), meaning that the trial starts. The position of this target is randomly distributed across 5 different locations that are equally spaced around a semicircle of 10cm radius, at 0, 45, 90, 135 or 180 degree from the Starting point. All those elements are represented in figure 2.5.

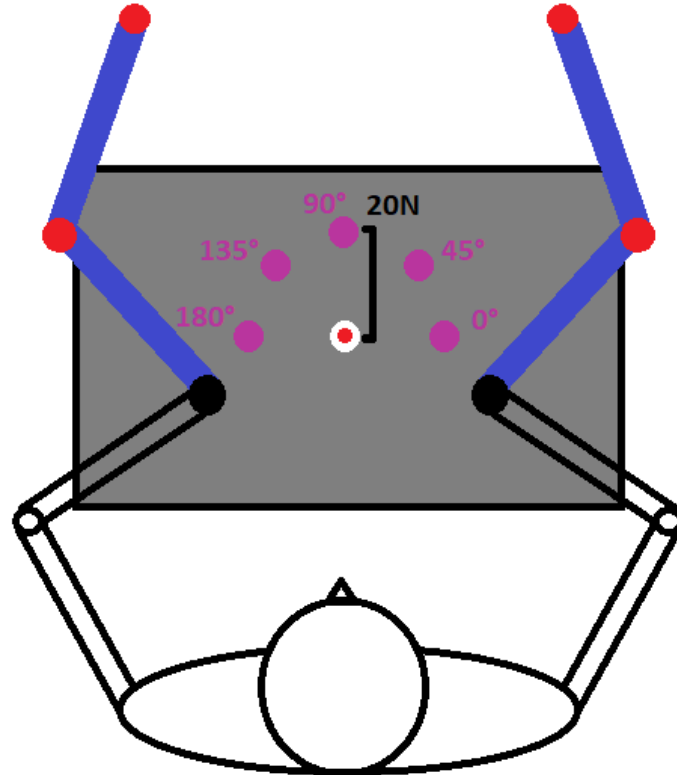


Figure 2.5: Experimental Setup showing the cursor to move (red), the Starting point (white) and the different possible targets (purple)

Once the target is reached, the participant has to stabilize the cursor inside of it for 1 second. When this condition is fulfilled, it is the end of the trial. The Target will then turn blue if the movement was too fast, green if the subject made the trial in the allotted time, and orange if it was too slow. This allows the participant to have a feedback on the speed of his movement, so that he makes most of the trials at the almost same speed.

Then, to start a new trial, the subject only has to stop the force production onto the robotic arms. Indeed, as said before, when no force is applied, the cursor returns to its initial position (into the Starting point), thanks to the force field. The subject has then to wait 1 second without producing any force to stay into this Starting point, which will launch the next trial. Different illustrations of all this can be found in figure 2.6.

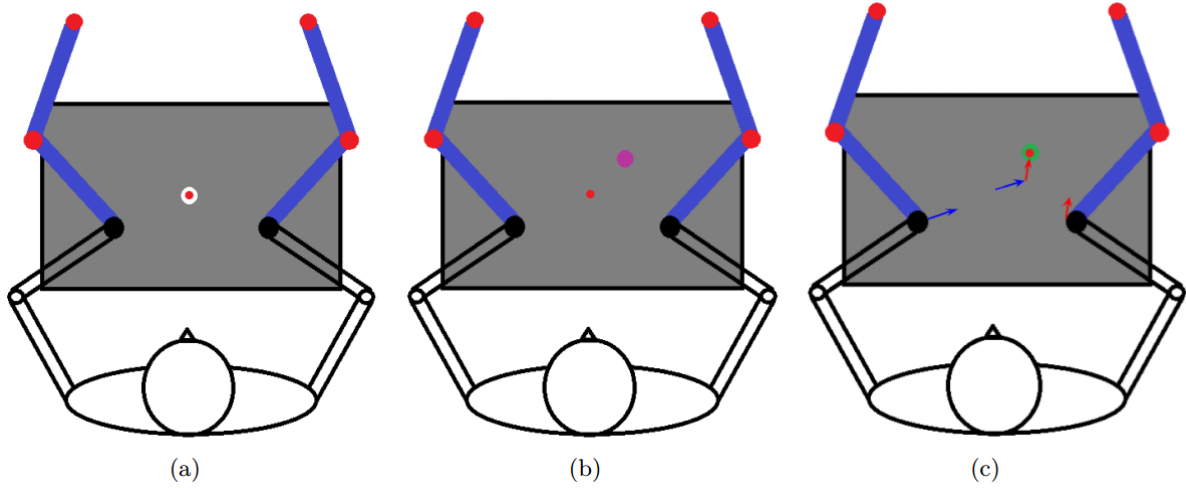


Figure 2.6: Experimental Setup representing different moments of the experiment : between two trials (a), at the beginning of a new trial towards the target located at 45° (b) and at the end of a successful trial (c)

In fact, different kinds of trial exist. The first one, that you just saw on figure 2.6, is the unperturbed trial. Secondly, trials with a visuomotor rotation will also be used. For this kind of trial, the projected target remains at the same location, but the cursor moved by the participant has its trajectory visually deflected. So, in order to reach the target, the participant will have to adjust his cursor movement. This leads thus to a new virtual force target. An example of this effect for a visuomotor rotation of 30 degree towards the left can be found in figure 2.7.

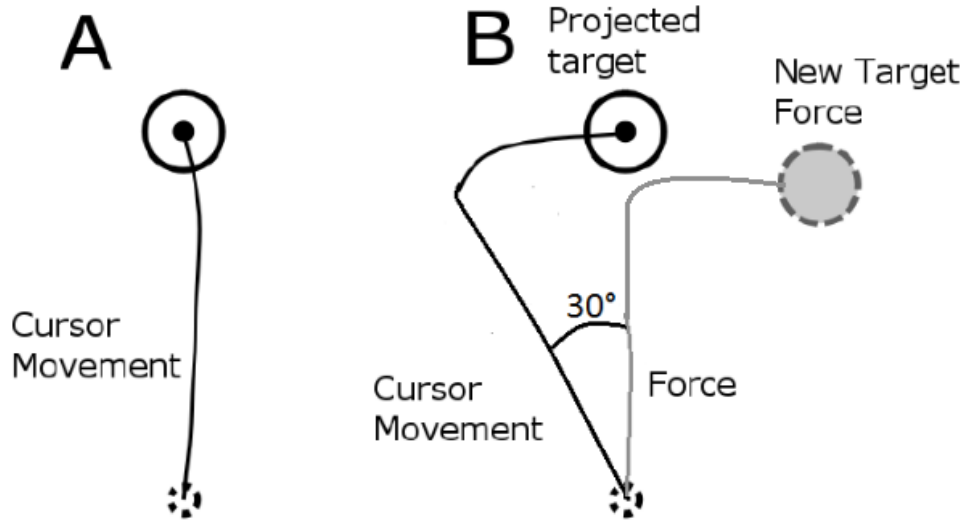


Figure 2.7: Cursor trajectory (black line) and the corresponding force produced by the subject (gray line) during an unperturbed trial (**A**) and a trial with 30° of visuomotor rotation towards the left (**B**). The target projected on the screen is presented as a black circle. After the visuomotor rotation, the cursor trajectory is deflected by 30°. The new target force after the visuomotor rotation is presented as a dashed gray circle and is also deflected by 30°, but remains at 20N from the starting point.

Then, a last kind of trial exists. In this third type, we decided to use a mix of two different perturbations : a visuomotor rotation and a cursor jump of variable amplitude. Here, the principle remains the same as for the second type, but the cursor moved by the participant will also encounter a sudden jump in his trajectory after a quarter of the movement. So, once again, even if the visually projected target remains at the same location, the corrections made by the participant will lead his movement to a new virtual force target. This can be seen in figure 2.8. It is also important to note that, for this specific kind of trial, the virtual force target do not stay exactly at a distance of 20N from the starting point. Indeed, for cursor jumps of 5cm for example (which is already an important value since it corresponds to one half of the distance between the starting point and the visual target), the new virtual target is located at a distance close to 22N from the starting point. So, during the analysis of the results obtained for this kind of trial, we decided to scale down these values to 20N in order to obtain results comparable with the other ones.

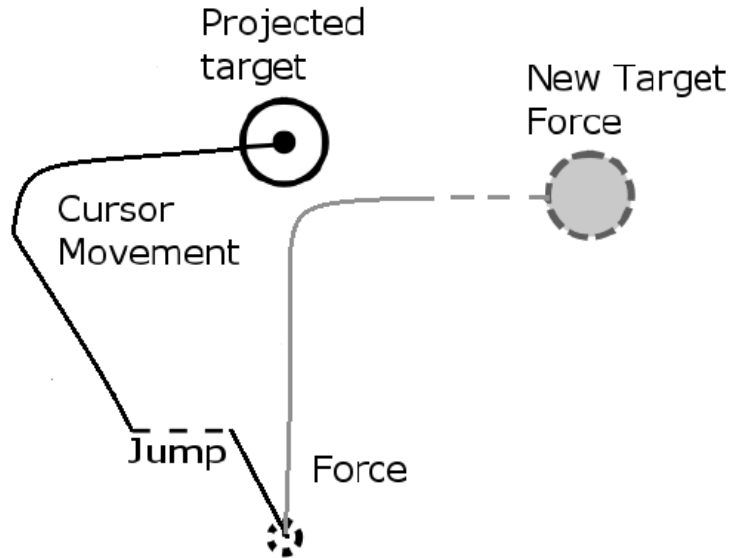


Figure 2.8: Cursor trajectory (black line) and the corresponding force produced by the subject (gray line) during a trial with the visuomotor rotation and the cursor jump towards the left. The target projected on the screen is presented as a black circle. After the visuomotor rotation, the cursor trajectory is deflected by 30° . The cursor jump takes place after a quarter of the movement. The new target force after both the visuomotor rotation and the cursor jump is presented as a dashed gray circle and is also deflected by 30° and moved by the amplitude of the cursor jump in the opposite direction.

With all this, we decided to cut each experiment into 3 different blocks.

The first block is a block composed of 80 trials. The task asked to the participant during all these trials is an unperturbed movement towards the randomly chosen target. The time needed to obtain a successful trial is between 500 and 800ms. This first block will allow us to know how participants react to our basic experimental task without any perturbation. It will then serve us to compare the results obtained during this block with the ones found in the next two blocks, when perturbations will be introduced.

The second block is made of 2 different kinds of trial. First of all, we will induce a progressive rotation of the visuomotor map from 0 to (+ or -) 30° . Since we do not want our subjects to notice this perturbation, we will introduce it very carefully. Steps of 0.5° will then be used, giving us 61 trials for the first part of this second block.

Then, when a visuomotor rotation of 30° is obtained, we will maintain it for 80 more trials in order to anchor the learning of this visuomotor rotation. The allotted time during this whole block stays between 500 and 800ms.

So, this second block, made of 141 trials in total, will allow us to see the impact that this hidden perturbation has on the behavior of our subjects.

Finally, when this is done, we can switch to the third block. Into this last block, we used our third kind of trial : the visuomotor rotation remains fixed to 30° , and we also introduce a cursor jump during the movement. This jump takes place when the cursor reaches $1/4$ of the distance between the Starting point and the Target (= 2.5cm) and is always perpendicular to the Target direction.

We will use 5 different cursor jumps : 5cm to the left, 3cm to the left, 3cm to the right, 5cm to the right and 0cm ("control trials"). The allotted time for this kind of trial is increased a little bit in order to allow the subjects to correct this perturbation. They have between 500 and

1000ms to reach the target. In order to have a good amount of results for each specific kind of perturbed trial (5 different targets x 5 different cursor jumps), we decided to make 250 trials in this third block.

So, this last block will allow us to see the effects that this other kind of perturbation has on the behavior of our subjects. Moreover, it will also enable us to compare these effects with the ones found into the previous block, where the visuomotor rotation is applied alone.

The whole experiment is thus made of $80 + 61 + 80 + 250 = 471$ trials. So, in order to keep the subject focused during our different blocks, we will make short breaks (around 60 seconds) between the blocks. Moreover, 3 other breaks will be added during the last block. Indeed, we decided to cut the 250 trials of this block into 4 parts : 75-75-50-50.

So, for example, a subject from the "left group" will have to do :

- Block 1 : 80 basic trials (no visuomotor rotation)
- Break
- Block 2.1 : 61 trials with gradual visuomotor rotation towards the left
- Block 2.2 : 80 trials with 30 degree of visuomotor rotation towards the left
- Break
- Block 3.1 : 75 trials with cursor jumps and 30 degree of visuomotor rotation towards the left
- Break
- Block 3.2 : 75 trials with cursor jumps and 30 degree of visuomotor rotation towards the left
- Break
- Block 3.3 : 50 trials with cursor jumps and 30 degree of visuomotor rotation towards the left
- Break
- Block 3.4 : 50 trials with cursor jumps and 30 degree of visuomotor rotation towards the left

The total duration of the experiment is around 40 minutes per subject.

CHAPTER 3

THE PROGRAMMING ENVIRONMENT

3.1 Custom Task Program

The Task Program is the chain of events that will happen during a single trial of the experiment. To define our trial protocol, we used a software specific to the KINARM Lab : Dexterit-E. It is a behavioral control and data acquisition software that runs the KINARM Lab on a Windows 7 computer through a real-time computer providing precise, reliable control and measurement of the system under study. This software, easy to take in charge, allows to rapidly implement a lot of different kinds of research protocols.[21]

Task Programs are created outside of Dexterit-E, using Simulink and Stateflow. Simulink is a block diagram environment for multidomain simulation and Model-Based design. It provides a graphical editor, customizable block libraries and solvers for modeling and simulating dynamic systems. It is the programming environment in which Task Programs are developed by a graphical representation of data flow in the task.[23]

Stateflow is an environment for modeling and simulating combinatorial and sequential decision logic based on state machines and flow chart. Stateflow allows to combine Stateflow Charts, flowcharts in which events and independent system states are defined, to model how the system reacts to events, time-based conditions and external input signals.[24]

Finally, Dexterit-E also allows to view collected data on a trial-by-trial basis on Dexterit-E Explorer, and to export data for analysis in MATLAB. [21]

3.2 Mathworks' Simulink

The first thing to do in order to implement our Custom Task in the Dexterit-E environment was to create, arrange and link all the Simulink blocks required. All the blocks used in our case can be seen in figure 3.1.

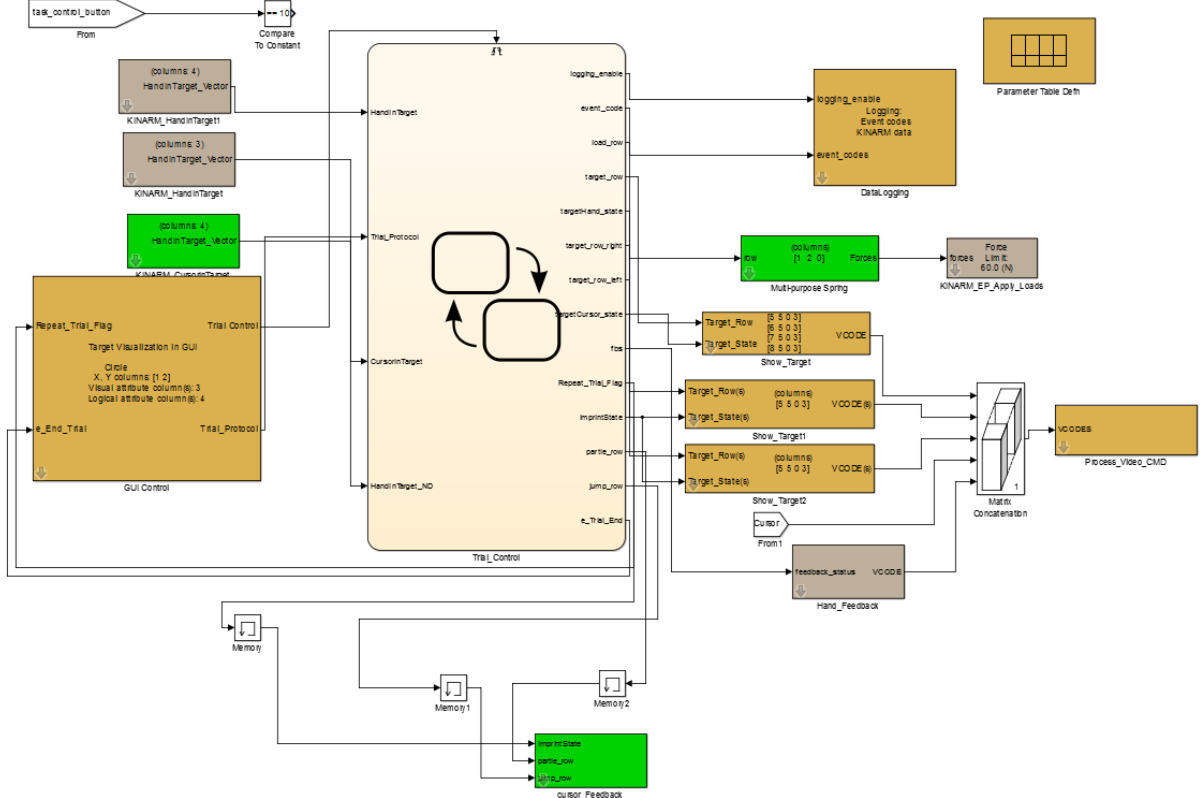


Figure 3.1: Simulink model used for our Custom Task

First of all, the "GUI Control" block makes the link between the two custom computers (Windows 7 computer for the Dexter-E and real-time one to run the Custom Task Program). It is also the block that controls the sequence of trials. For each trial, it receives feedback from the Stateflow Chart, and returns the appropriate Trial Protocol in exchange. Visualization of the different targets used in our experiment is done thanks to the "Show_Target" block. This block simply creates a visual command for the targets, called VCODE, that will be used in the "Process_Video_CMD" block. "Hand_Feedback" and "cursor_Feedback" blocks work the same way, except that their VCODEs will be used for the hand feedback and cursor feedback shown to the subject during the experiment. The sub-blocks used for those two feedbacks can be seen in figure 3.2.

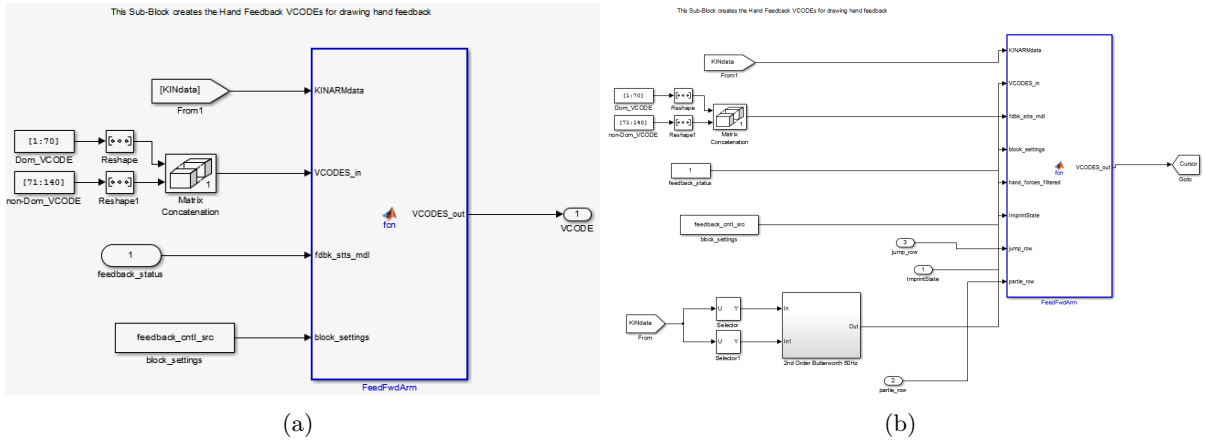


Figure 3.2: Hand_Feedback sub-blocks (a) and cursor_Feedback sub-blocks (b)

Moreover, the FeedFwdArm sub-block represented in figure 3.2 b is also the place where we coded the visuomotor rotation and the cursor jump. Indeed, to do so, the only thing to change is the cursor displacement, which is implemented there.

For the visuomotor rotation, we used our new parameter "partie_row". This parameter represents the degree of the visuomotor rotation, with values going from 0 to 61 during the implementation of the gradual visuomotor rotation, allowing us to go from 0 to 30 degree of rotation. So, when the visuomotor rotation is fixed to 30 degree, we also kept the value of this parameter to 61. The part of Matlab code used to implement the visuomotor rotation towards the right is rewritten in the equations just below. Note that the code for the visuomotor rotation towards the left is the same, only the "+" and "-" are inversed.

$$F_X = (F_{RX} + F_{LX}) * \cos(partie_row) - (F_{RY} + F_{LY}) * \sin(partie_row) \quad (3.1)$$

$$F_Y = (F_{RY} + F_{LY}) * \cos(partie_row) + (F_{RX} + F_{LX}) * \sin(partie_row) \quad (3.2)$$

with

- F_X the total horizontal force
- F_Y the total vertical force
- F_{RX} the horizontal force produced by the right hand
- F_{LX} the horizontal force produced by the left hand
- F_{RY} the vertical force produced by the right hand
- F_{LY} the vertical force produced by the left hand
- $partie_row$ the parameter used to represent the degree of the visuomotor rotation

Similarly, for the cursor jumps, we used a new parameter "PerturbationCm" that defines the amplitude of the cursor jump (5, 3, 0, -3 or -5 cm). This allowed us to implement the desired cursor jump in the desired direction opposed to the target direction and after 2.5 cm in the movement (corresponding thus to 1/4 of the total movement).

Finally, the last important block is the "Parameter Table Defn". This table contains all the parameters and constants that we will use into our experimental task. For example, figure 3.3 shows the different parameters that we used for our experiment. Values for those parameters can be decided and change on the BKIN Dexterit-E program that runs the KINARM. Figures representing the different events that can happen and the parameters of the targets used, as well as their associated description, can be found in the Appendix B.

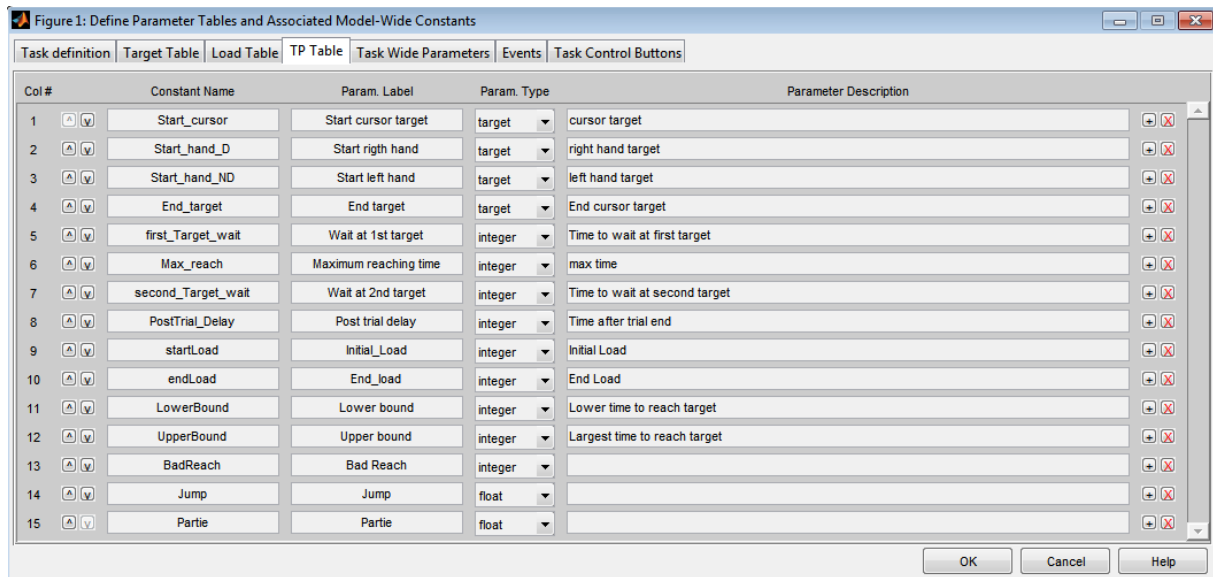


Figure 3.3: TP Table filled into the 'Parameter Table Defn'

3.3 Stateflow chart

As said before, in order to define our Custom Task Program, we combined Stateflow Charts in which we model how the system reacts to events, time-based conditions and external input signals. This is done into the "Trial_Control" block of Mathworks' Simulink that can be found in figure 3.1.

Figure 3.4 shows our Stateflow chart defining what will happen in a single trial. The rectangles, representing the different states, are connected by blue arrows that matches to the transitions between states.

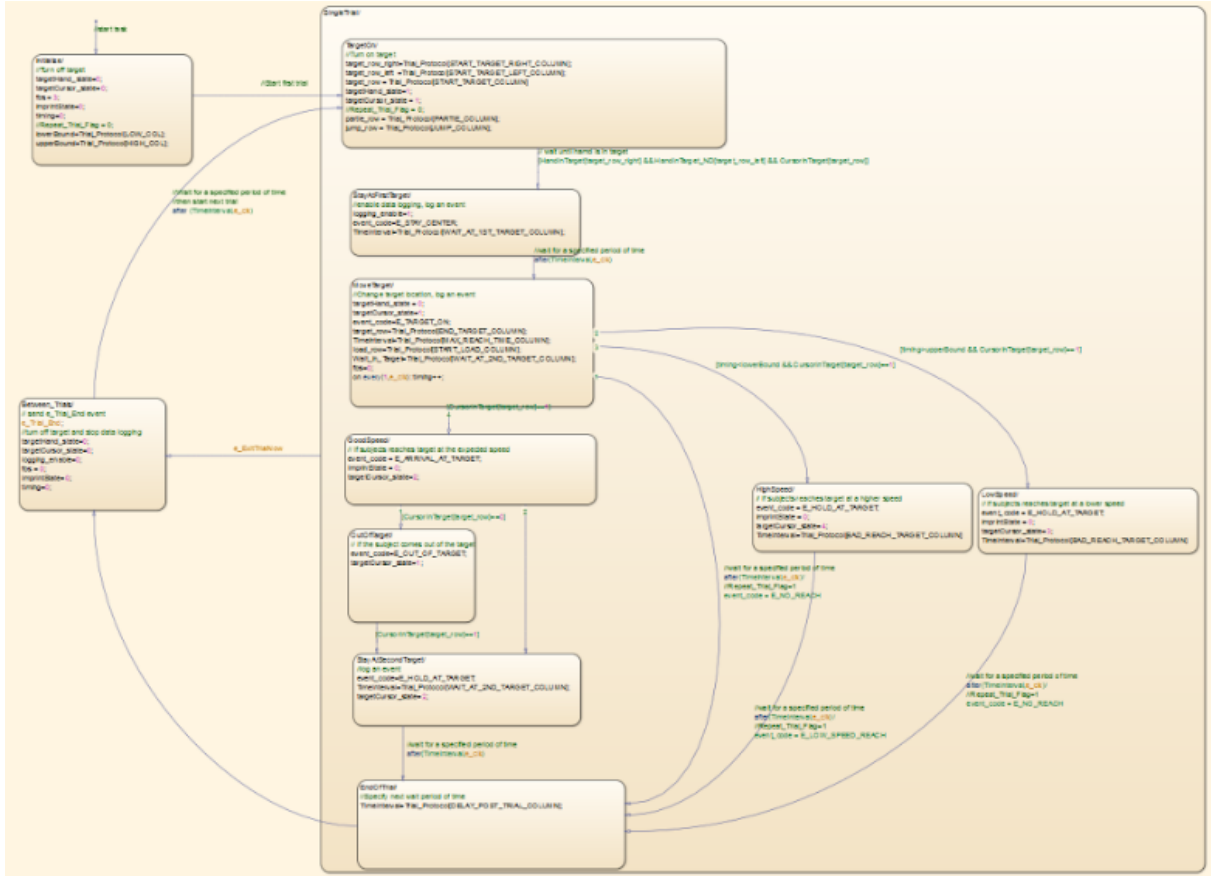


Figure 3.4: Stateflow Chart of each trial of the experiment

So, the task can be summarized by the steps below, that can be found in figure 3.4 :

1. As shown in figure 3.5, the first step is the initialization step. This step only takes place when the Task Program is loaded. It initializes the timing and turns off the target.

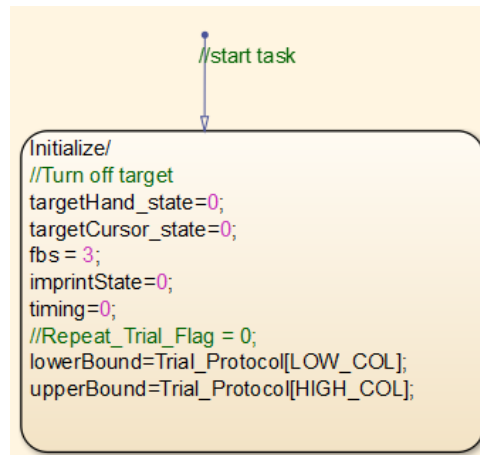


Figure 3.5: First step of the Stateflow Chart

2. The second step, as shown in figure 3.6, represents the beginning of a trial. Starting point and cursor feedback are available, and this step keeps going until the cursor is brought into the Starting point.

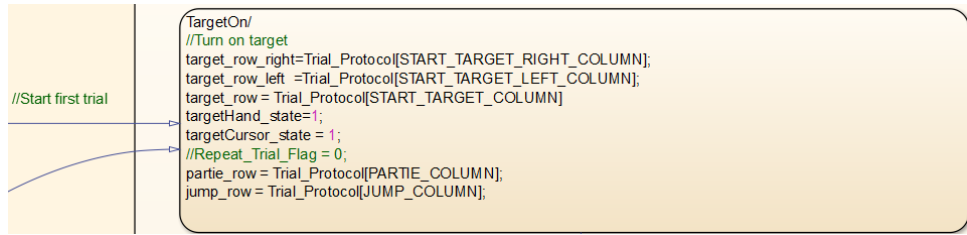


Figure 3.6: Second step of the Stateflow Chart

3. Into this third step, the subject only has to wait for a specified period of time, that we defined as 1000ms, with the cursor into the Starting point. This step, shown in figure 3.7, allows to have relaxed forces at the beginning of the movement towards a target (in the next step).

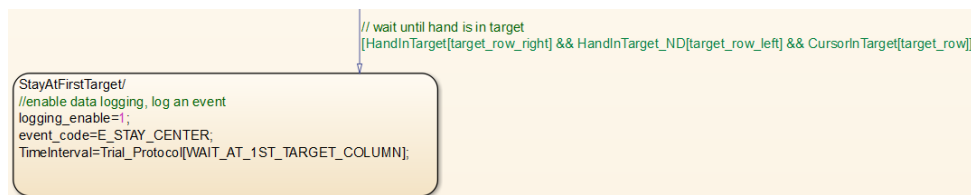


Figure 3.7: Third step of the Stateflow Chart

4. When the specified period of time ends, we can move to the fourth step represented in figure 3.8. In this step, the Starting point disappears, while the target appears. The subject has then 3000ms to reach the target.

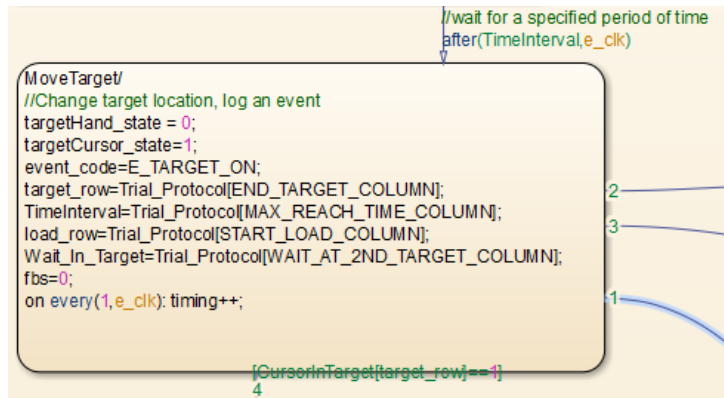


Figure 3.8: Fourth step of the Stateflow Chart

5. According to the time needed to reach the target, 4 different possibilities exist, as shown in figure 3.9.
 - 5.1. The target has not been reached after 3000ms. In that case, we directly go to the end of the trial.
 - 5.2. The target has been reached too slowly. In that case, the target turns into a specific color, defined here as orange. Then, when the cursor has been held in the target for 1000ms, the program continues to the end of the trial.
 - 5.3. The target has been reached too fast. In that case, the target turns into a specific color, defined here as blue. Then, when the cursor has been held in the target for 1000ms, the program continues to the end of the trial.

- 5.4. The target has been reached within the allotted time. In that case, the target turns into a specific color, defined here as green. Then, when the cursor has been held in the target for 1000ms, the program continues to the end of the trial.

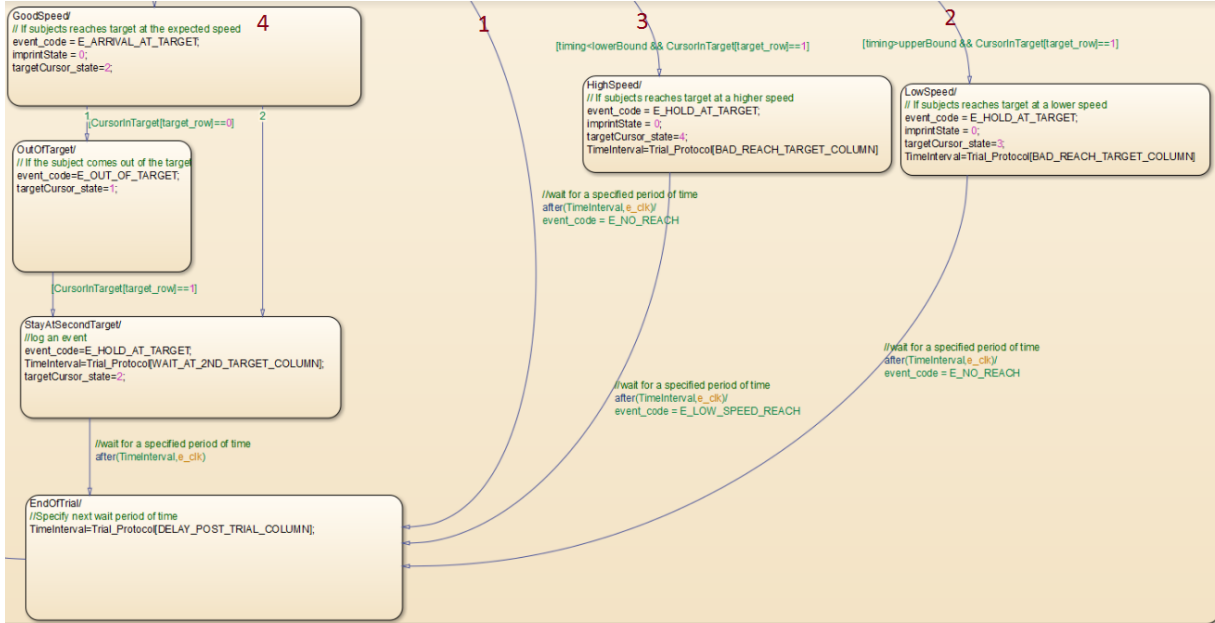


Figure 3.9: Fifth step of the Stateflow Chart

6. The last step of our Custom Task is, as represented in figure 3.10, the "Between Trials" step. This last part simply allows to reset the different values (like the timing for example), but also to wait for a specified interval of time before launching the next trial. We chose 500ms for this interval.

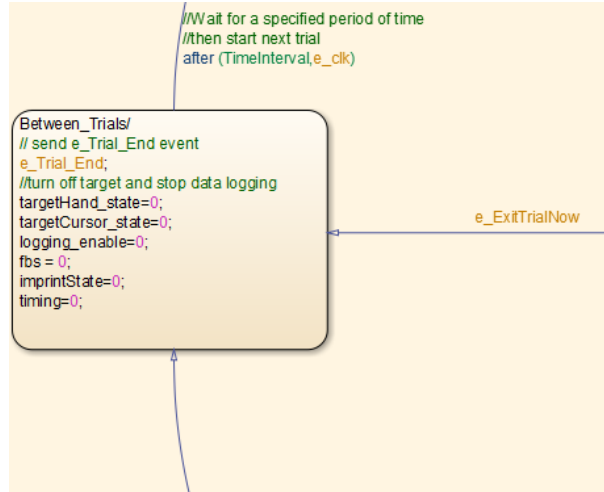


Figure 3.10: Last step of the Stateflow Chart

3.4 BKIN Dexterit-E

Finally, when the Custom Task Program has been made, it can then be downloaded under the BKIN Dexterit-E, which is the software that runs the KINARM. So, this software will only use the program previously built thanks to Mathworks' Simulink and the Stateflow Chart.

It is also in the Dexterit-E software that you can edit your task protocol by choosing and implementing the values of the different parameters used. For example, figure 3.11 shows the target table that we used for our whole experiment, while figure 3.12 gives a part of the TP Table of the block 2 of our experiment, showing the values of the most important parameters.

Target Table

X: X Position (cm) of the target relative to local (0,0)

	X	Y	VRad	LRad	Color	Second Color	High speed Color	Low speed Color
Target 1	7.000	4.000	1.000	1.000	Red	Green	Black	Black
Target 2	-7.000	4.000	1.000	1.000	Red	Green	Black	Black
Target 3	0.000	15.000	1.000	0.500	Red	Green	Cyan	Yellow
Target 4	-10.000	15.000	1.000	0.500	Purple	Green	Orange	Blue
Target 5	-7.071	22.071	1.000	0.500	Purple	Green	Orange	Blue
Target 6	0.000	25.000	1.000	0.500	Purple	Green	Orange	Blue
Target 7	7.071	22.071	1.000	0.500	Purple	Green	Orange	Blue
Target 8	10.000	15.000	1.000	0.500	Purple	Green	Orange	Blue
Target 9	0.000	0.000	0.000	0.000	Blue	Green	Cyan	Yellow
Target 10	0.000	0.000	0.000	0.000	Blue	Green	Cyan	Yellow

Figure 3.11: Dexterit-E's Target Table. Target 1 and 2 represent the positions of the two robotic hands. Targets 4 to 8 are the different possible targets to reach.

TP Table

Start cursor target: cursor target

	Start cursor target	Start right hand	Start left hand	End target	Wait at 1st target	Lower bound	Upper bound	Bad Reach	Jump	Partie
TP 2	32	1	2	4	1000	500	800	1000	0.000	0.000
TP 3	32	29	30	8	1000	500	800	1000	0.000	1.000
TP 4	32	29	30	8	1000	500	800	1000	0.000	2.000
TP 5	32	29	30	7	1000	500	800	1000	0.000	3.000
TP 6	32	29	30	4	1000	500	800	1000	0.000	4.000
TP 7	32	29	30	7	1000	500	800	1000	0.000	5.000
TP 8	32	29	30	6	1000	500	800	1000	0.000	6.000
TP 9	32	29	30	8	1000	500	800	1000	0.000	7.000
TP 10	32	29	30	7	1000	500	800	1000	0.000	8.000

Figure 3.12: Part of Dexterit-E's TP Table (Block 2). The progressive visuomotor rotation is introduced by step of 0.5° , thanks to the parameter "Partie". The parameter "Jump" is here fixed to 0, since there is no cursor jump in this block of the experiment. It will be used for the cursor jumps during the third block.

Dexterit-E is also where we defined the different blocks of our experimental task, as shown in figure 3.13. We can see that our block 2 is made of 61 trials following a certain order for the progressive visuomotor rotation and then 16 repetitions of 5 randomized trials that stand for the 5 possible targets with the fixed visuomotor rotation.

Edit Task Protocol (Block 2.1 D)					
General	Target Table	Load Table	TP Table	Task Wide Params	Block Table
Block Table					
TP List: List of trial protocols to include in the block.					
		List Reps	Catch TP List	Randomized	Block Reps
Block 1	2,3,4,5,6,7,8,9,10,11,[.....],53,54,55,56,57,58,59,60,61,62	1		☐	1
Block 2	64,65,66,67,68	16		☒	1
Block 3		0		☐	0
Block 4		0		☐	0
Block 5		0		☐	0
Block 6		0		☐	0
Block 7		0		☐	0
Block 8		0		☐	0
Block 9		0		☐	0

Figure 3.13: Dexterit-E's Block Table (Block 2). "Block 1" represents the first part of the block, in which the progressive visuomotor rotation is introduced during 61 trials, and "Block 2" is the second part, made of 80 trials with the visuomotor rotation fixed at 30°.

Dexterit-E's TP Table and Block table used for the first block of our experimental task can be found in the Appendix C.

CHAPTER 4

RESULTS

4.1 Validation of the experimental task

In this section, we will detail all the analysis that we made on the data collected from our 20 subjects, and results that we found from it.

First of all, we wanted to know if our experiment was adapted and not too hard to succeed. To do so, we analyzed the success rate of our experiment. A table with the success rate for all the different parts of our experimental task can be found in the Appendix D.

From the results, we found out that except for two subjects that seem to have more difficulties to realize the experiment, the task is quite well achieved. And even those two subjects have global success rate just below 70%, which remains quite good. The best participant almost reaches 95% of successful trials, and the mean is 83.5%, higher than we expected.

We can also notice that in general, the cursor jump induces some failed trials during the first part of the last block (Jump1) because the subjects are not used to this perturbation. But we can see that, for the other parts of this last block (Jump2, 3 and 4), the success rate increases. Indeed, the subjects show habituation to this perturbation, allowing them to know how and how fast to react when they face a cursor jump. Some participants were even able to achieve a perfect part of the last block, completing successfully a set of 50 or 75 trials.

Moreover, none of the subjects noticed the hidden visuomotor rotation. From all this, we concluded that our experiment was well built, adapted and not too hard to realize, and so, that no modification was required.

Once we confirmed the feasibility of our experimental task, we started to focus on analysis that would allow us to answer our research question : *"How is responsibility assigned in a redundant system during a bimanual task ?"*.

So, as first, we decided to build the Force Production Map, or FPM, for our 20 subjects during the initial condition of our experiment, which means the first block of 80 trials. The so called FPM represents the distribution of forces for both hands at the end of the movement of our experiment, when the subject stabilizes the cursor into the target.

So, to build this FPM, we have chosen to use the mean of force produced by each hand in the 300ms interval [End of the trial - 500ms ; End of the trial - 200 ms]. Since the time corresponding to the end of the trial will be different for each trial, this interval will also change. This allows to always remain in an interval which is well-adapted for our analysis : not too close to the end of the trial, but also late enough after the target reach. Thanks to this, we are sure that the

subject is already well stabilized into the target, and we also avoid bias that could be introduced if the subject relaxed the forces he applied on the handles a little bit too early.

Figure 4.1 illustrates this for a single trial of one subject. Naturally, the trials are separated according to their target direction. This method is the one that we used to produce all the Force Production Maps that we will present during this work.

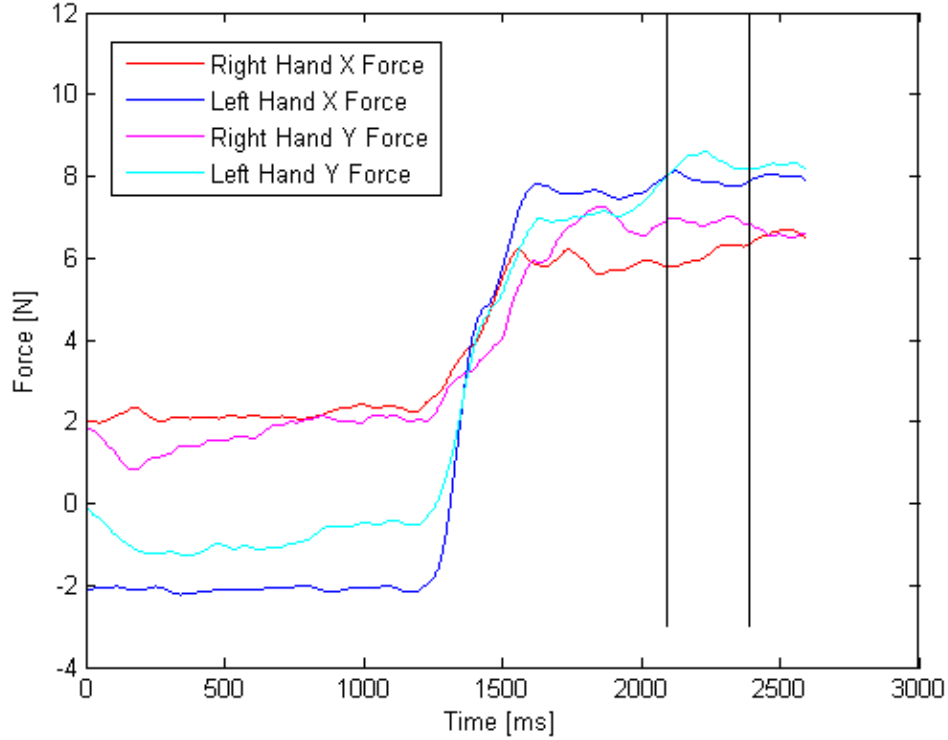


Figure 4.1: Time evolution of the X and Y forces for both hands for a trial towards the target located at 45° . The interval used to build the force production maps is represented by the black lines. It starts 500ms before the end of the trial and lasts for of 300ms. 4 different means are then calculated with the values of the different forces in this interval (colored lines), and these 4 means are then used as coordinates for the FPM.

Since the task to realize during our initial condition is the same as David Cordova during his own experiment, except that we restrained the task into one hemichamp instead of the whole visual field, we expected to get results really close to the ones that he found [19]. Those two FPM can be found in figure 4.2.

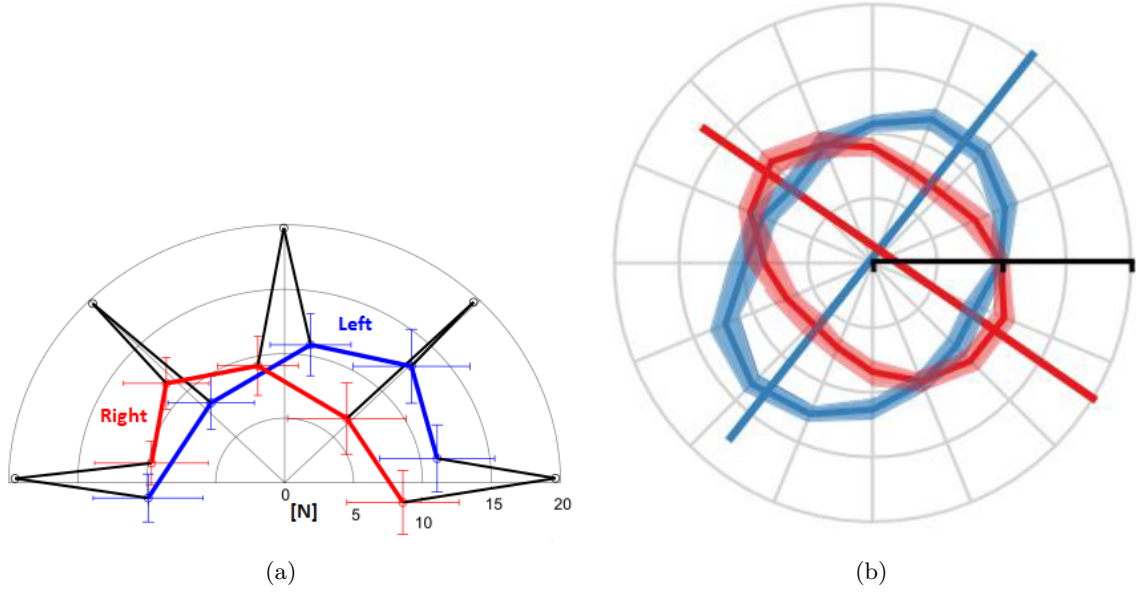


Figure 4.2: Force Production Map for the first block of our experiment (a) and Force Production Map obtained by David Cordova during his experiment (b) [19]. Blue stands for the left hand, while red represents the right hand and black lines show the different targets. Since we used a bimanual task, each virtual target corresponds to a sum of force contribution of the right and left hand.

From those figures, we can see that, as expected, the shape obtained for the FPM from the first block of our experimental task is really close to the shape obtained by David Cordova during the standard task of his own experiment. It can be noticed that, in both cases, the subjects tend to use preferentially their left hand to reach targets located to the right, and their right hand for the targets on the left. And this tendency is the most notable around 45 and 135 degree, and decreases when the direction of force production changes. So, this is consistent with what has been found in the previous study of David Cordova, and shows that the preferential directions of force production are well preserved [19].

This result allows us to be sure that the first block of our experimental task matches well the standard task of David Cordova, as we wanted. But the comparison with his work ends here, since the purpose of our work is to find the effect that the visuomotor rotation induced gradually during our second block and still active during our third block will have on the behavior of our subjects.

4.2 Left visuomotor rotation

So, to analyze the effect of the visuomotor rotation, we firstly split our 20 subjects into 2 groups of 10, as already said before. For the first group, a visuomotor rotation towards the left was used during the experiment. Then, in order to visualize the effect that this visuomotor rotation towards the left will have on the force production of our subjects, we decided to rebuild the FPM of those 10 subjects after that this visuomotor rotation has been anchored, which means at the end of the second block, and to compare it with the FPM found in the first block, where this visuomotor rotation is not yet induced. Figure 4.3 represents those two FPM.

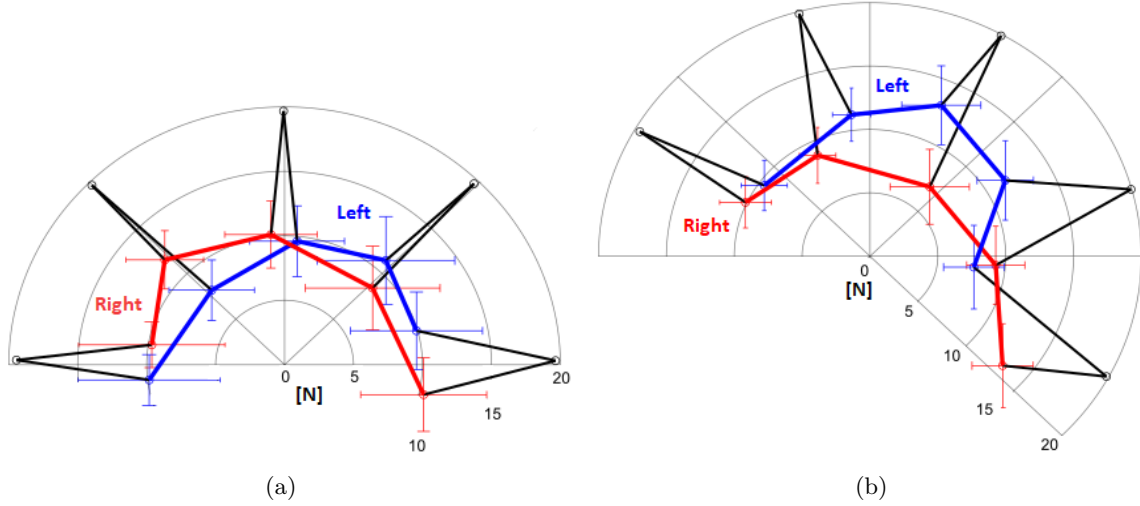


Figure 4.3: Force Production Map for our first group of subjects before (a) and after (b) the left visuomotor rotation. Blue stands for the left hand, while red represents the right hand and black lines show the different virtual targets. Since we used a bimanual task, each virtual target corresponds to a sum of force contribution of the right and left hand.

But, before analyzing this figure, two things are important to note. First of all, we can see that figure 4.3 a is not exactly the same as figure 4.2 a, even if they are really close to each other. This small difference is due to the fact that the first figure was made for our 20 subjects, so the two groups together, while the second figure only comes from the group of 10 subjects that will undergo the visuomotor rotation towards the left.

Secondly, we can also notice that the location of the end-points of the movements of our subjects is not the same before and after the visuomotor rotation. This comes from the fact that, even if the subject is not aware of it, the visuomotor rotation leads to a change in the movement. Indeed, the projected targets after the visuomotor rotation remain at the same visual position, while the real cursor trajectory is deflected. So, subjects will have to compensate for this deviation in order to reach the target (see chapter Methods, figure 2.7). It is this effect that can be seen on figure 4.3 b, and that will also be present on other many other figures.

Besides that, we can also see that the visuomotor rotation towards the left has a huge impact on the distribution of force produced by our hands to reach the different targets. Before the visuomotor rotation, the maximal force produced did not exceed 12N for the right hand and 11N for the left hand, proving that both hands participate almost equally to the movement. We can notice that it completely changes after that this visuomotor rotation has been anchored. Indeed, figure 4.3 b shows that, for some targets, the distribution of force production is almost 75% for one hand and 25% for the other one. It can also be noticed that the preferential directions of force production found by David Cordova during his work and partially re-obtained during our first block of the experimental task seem to remain. But it also looks like they were amplified and moved of a few degrees during the visuomotor rotation, since the location of the most important difference in the force production distribution can be found near those directions.

Finally, it is also interesting to see that, to reach the target visually located horizontally towards the right, participants use more their right hand than their left one. Furthermore, it is the only target for which our subjects use preferentially their right hand after the implementation of the visuomotor rotation. But this is also consistent with what has been stated just before, since it corresponds to the preferential direction of the right hand found by David Cordova [19]. We just did not find it in our initial condition because this direction of force production remained unexplored.

Moreover, when we do the same analysis on the third block of our experimental task for our first group of subjects (visuomotor rotation fixed to 30 degree towards the left + cursor jumps), we can see that a sudden jump in the position of the cursor during the reaching movement of the subject also plays a role on the way forces are distributed across the two hands.

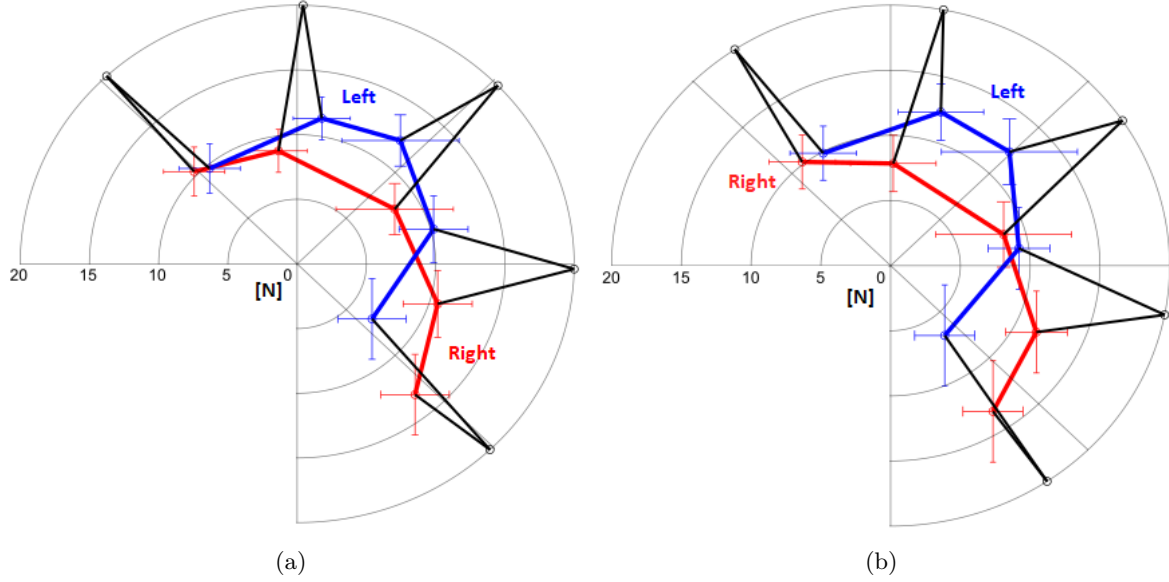


Figure 4.4: Force Production Map for our first group of subjects after the left visuomotor rotation and 3cm (a) or 5cm (b) cursor jump towards the left. Blue stands for the left hand, while red represents the right hand and black lines show the different virtual targets. Since we used a bimanual task, each virtual target corresponds to a sum of force contribution of the right and left hand.

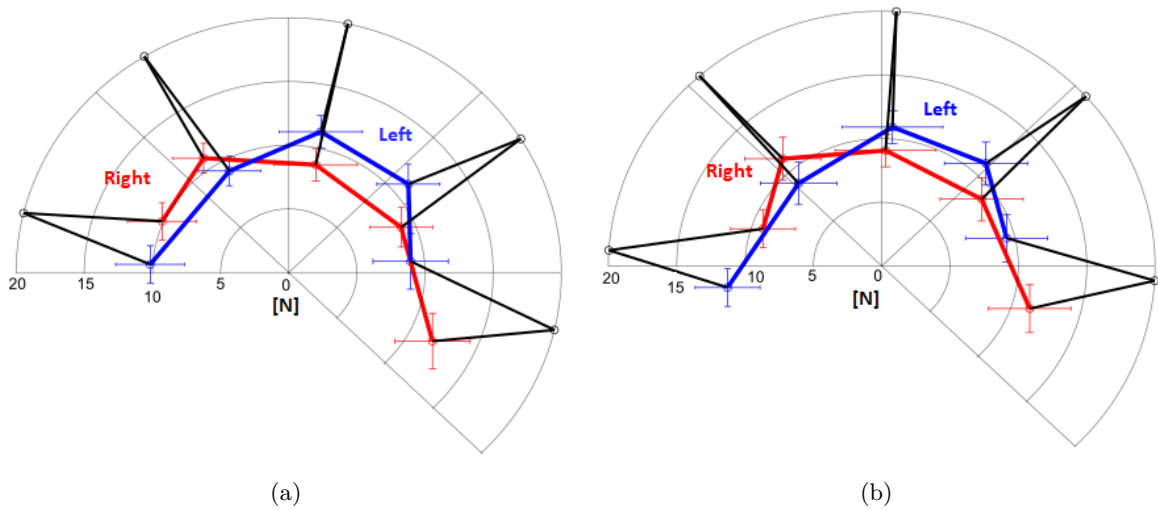


Figure 4.5: Force Production Map for our first group of subjects after the left visuomotor rotation and 3cm (a) or 5cm (b) cursor jump towards the right. Blue stands for the left hand, while red represents the right hand and black lines show the different virtual targets. Since we used a bimanual task, each virtual target corresponds to a sum of force contribution of the right and left hand.

First of all, it is once again important to notice that the cursor jumps, just as explained previously for the visuomotor rotation, have an effect on the positions of the end-points of force production. Even if the visual targets remained at the same position for the subject during the experiment, the movement produced to reach them is once again altered by those sudden jump of the cursor position. This leads to new virtual force targets, as previously explained (see chapter Methods, figure 2.8).

Moreover, figure 4.4, which shows the effect that cursor jumps towards the left have on the distribution of force production after that the visuomotor rotation towards the left has been anchored, and figure 4.5, which shows the effect of cursor jumps towards the right, are both really different. Note that the figure representing the effects of cursor jumps with an amplitude of 0cm, which is relatively similar to figure 4.3 b, can be found in the Appendix E.

Indeed, in figure 4.4, we can see that the effect of cursor jumps in the same direction than the already applied visuomotor rotation is relatively inconspicuous. The pattern of force production remains almost exactly the same as in figure 4.3 b. The only notable difference is the shift of position for the end-points, but that has been explained just before.

On the other hand, figure 4.5 shows that the impact of cursor jumps in the direction opposed to the direction of the visuomotor rotation applied is really different. Instead of keeping a shape close to the one obtained for the visuomotor rotation alone, the addition of cursor jumps in the direction opposed to the visuomotor rotation seems to bring us back to the initial case without any visuomotor rotation that can be found in figure 4.2 a. At least, some characteristics are the same. We obtain the same pattern of forces, and the difference of forces produced by each hand to reach the targets is reduced. The preferential directions of both hands can also be found, even if they are not located at the exact same location than during the first block.

Finally, figures a and b are, in both cursor jumps cases, showing the effect that the amplitude of those cursor jumps have on the distribution of force production for our subjects. And we can notice that this effect is really small. Except a small displacement of the end-points, as already explained, not much changes with the cursor jump amplitude. The shape of the figures remains almost the same, just making some discrete adjustments to match with the new virtual targets.

After that, in order to find out more about the effects of the visuomotor rotation and cursor jumps on the way subjects distribute forces across their two hands, we made a last analysis concerning those FPM. For each subject and each condition of our experiment (with or without visuomotor rotation and cursor jump), we have taken measurements of the two areas formed by the curves representing the contribution of each hand into the corresponding FPM. Then, we kept the mean for our 10 subjects. And finally, to be able to know the effects of the different conditions compared to the initial one, without any cursor jump nor visuomotor rotation, we normalized the obtained values of the different areas by the values of the areas found for our first block of trials. This analyze will then allow us to find out if there is a difference in the total amount of force produced by each hand, and if one hand is specifically preferred or not. Results can be found on figure 4.6.

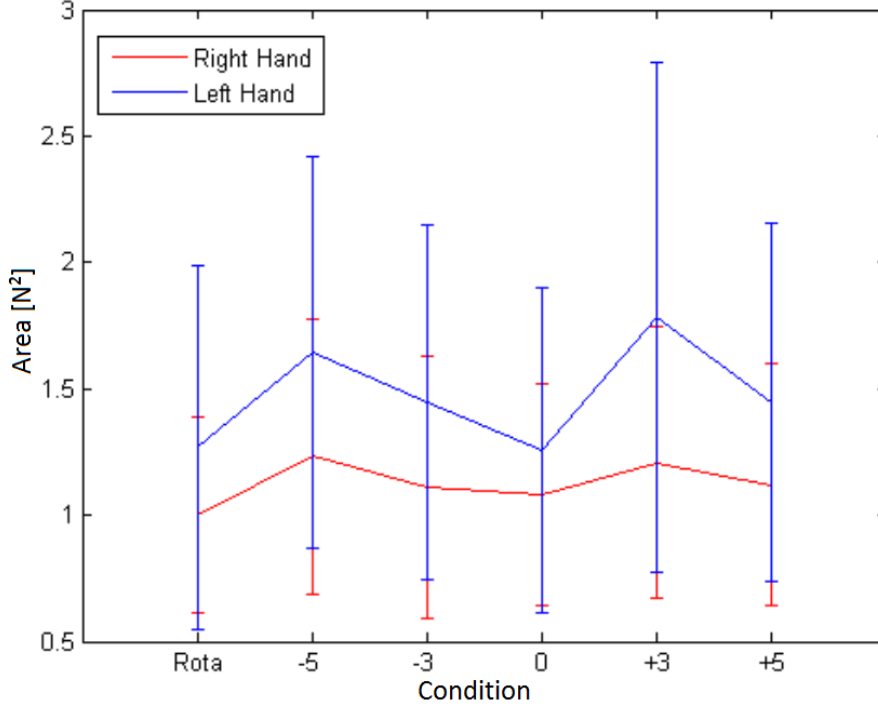


Figure 4.6: Mean and standard deviation of the areas of the left (in blue) and right (in red) hands of the FPM found for our first group of subjects, normalized by the values obtained for the area of the initial condition, for different conditions of the experiment. Rota stands for the end of the second block, when the visuomotor rotation has just been fixed to 30° towards the left, while the five other conditions represent the different amplitudes of cursor jumps that can be faced during the third block of our experimental task ("- is for the cursor jumps towards the left, "+" is towards the right).

And from this figure, we can see that the left hand acquires a huge importance after the visuomotor rotation towards the left. On the other hand, the contribution of the right hand remains almost the same, even if we saw before that it is differently distributed. The introduction of cursor jumps also has an impact. We can notice that both hands are more used, in an almost similar way to answer the introduction of cursor jumps in the same direction as the visuomotor rotation, and with a small preference for the left hand when the cursor jumps are opposed to the direction of the visuomotor rotation. Finally, we can also see that, for cursor jumps of 0cm (control trials used during the third block), the contribution of each hand is really close to the one found when no cursor jump at all was present (during the second block of the experiment).

4.3 Right visuomotor rotation

After that, we wondered if these effects were conserved for the visuomotor rotation in the other direction, or if the results were completely different. So, we made the same analysis on our second group of 10 subjects that experimented the visuomotor rotation towards the right. First of all, we began once again by comparing the FPM that we obtained for this second group before and after the visuomotor rotation. Figure 4.7 represents these two FPM.

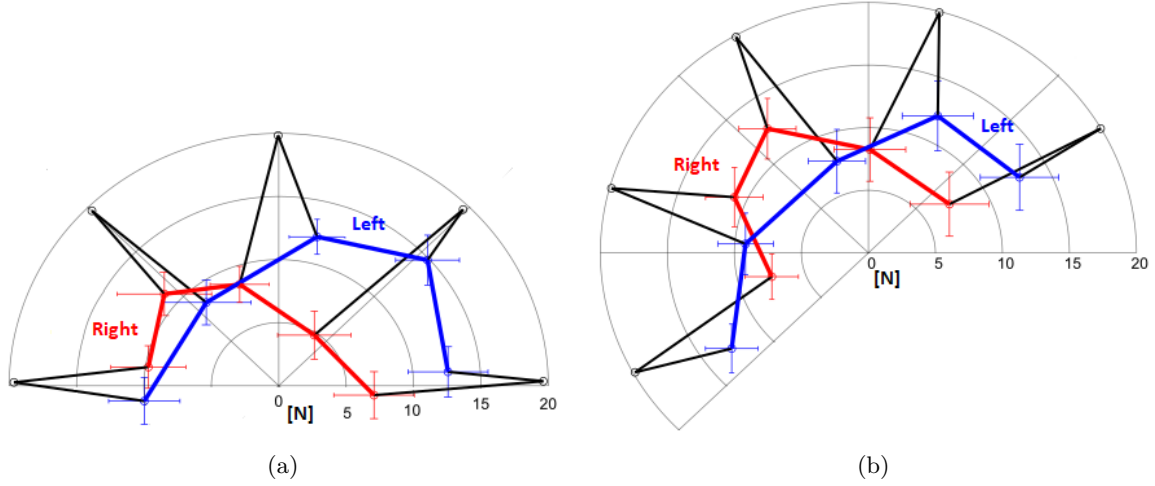


Figure 4.7: Force Production Map for our second group of subjects before (a) and after (b) the right visuomotor rotation. Blue stands for the left hand, while red represents the right hand and black lines show the different virtual targets. Since we used a bimanual task, each virtual target corresponds to a sum of force contribution of the right and left hand.

The first thing that we can notice is that this second group of participants uses the left hand for the initial condition way more than the first group. Indeed, if we compare figure 4.7 a with figure 4.3 a, we can see that the preferential directions of force production are once again respected even if moved of a few degrees, but also that the repartition of forces into the two hands is different. For our second group, the left hand is significantly favored to reach 3 of the 5 targets while it was only the case for the target located at 45° for our first group. Moreover, for this second group, the difference in force production of each arm in the same direction reaches a maximum of 10N, which is much higher than it was for the first group.

Then, if we analyze the effects of the right visuomotor rotation on the distribution of force production for this group of subjects, we can see that the preferential direction of the right hand is this time amplified. On the other hand, the contribution of the left hand is reduced for all the targets, except for the last one. This last target is indeed virtually located at 30° in the lower hemichamp, and thus closer to the preferential direction of the left hand than it was before the visuomotor rotation. On the other side, the preferential direction of the left hand into the upper hemichamp is also conserved, even if it is less marked.

After that, we once again analyzed the effects of a sudden jump in the position of the cursor. To do so, we realized the force production maps of the different conditions of the last block of our experimental task. Results are separated according to the direction of the cursor jumps, and can be found in figures 4.8 and 4.9. The first figure shows thus the effect that cursor jumps towards the right combined to the visuomotor rotation in the same direction have on the distribution of force production between the hands, while figure 4.9 shows the impact of cursor jumps in the opposite direction. Once again, the figure representing the effects of cursor jumps with an amplitude of 0cm, which is relatively similar to figure 4.7 b, can be found in the Appendix E.

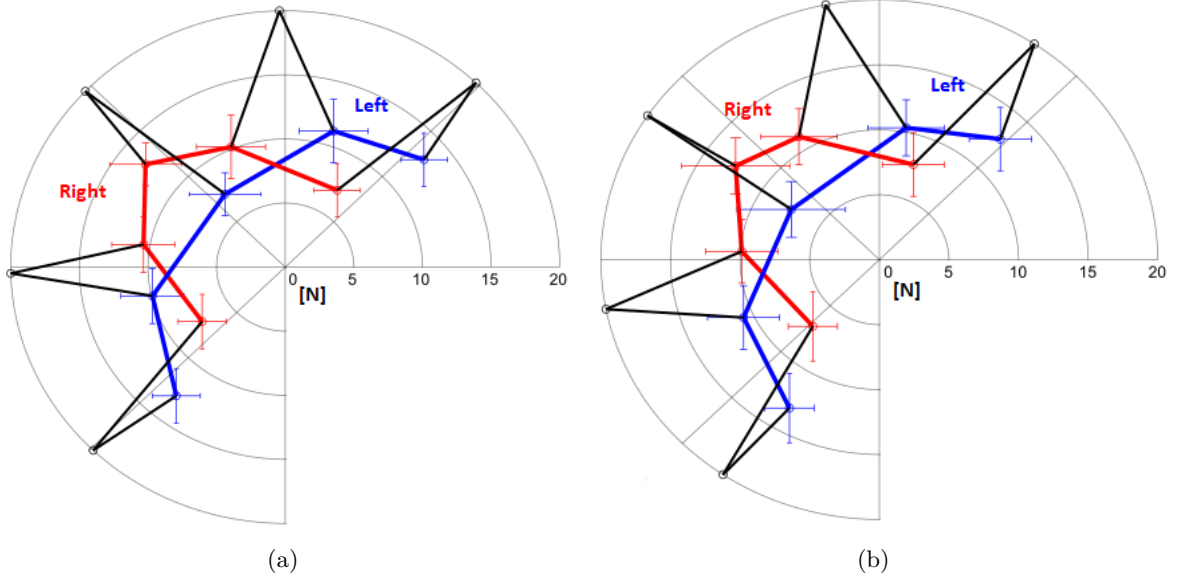


Figure 4.8: Force Production Map for our second group of subjects after the right visuomotor rotation and 3cm (a) or 5cm (b) cursor jump towards the right. Blue stands for the left hand, while red represents the right hand and black lines show the different virtual targets. Since we used a bimanual task, each virtual target corresponds to a sum of force contribution of the right and left hand.

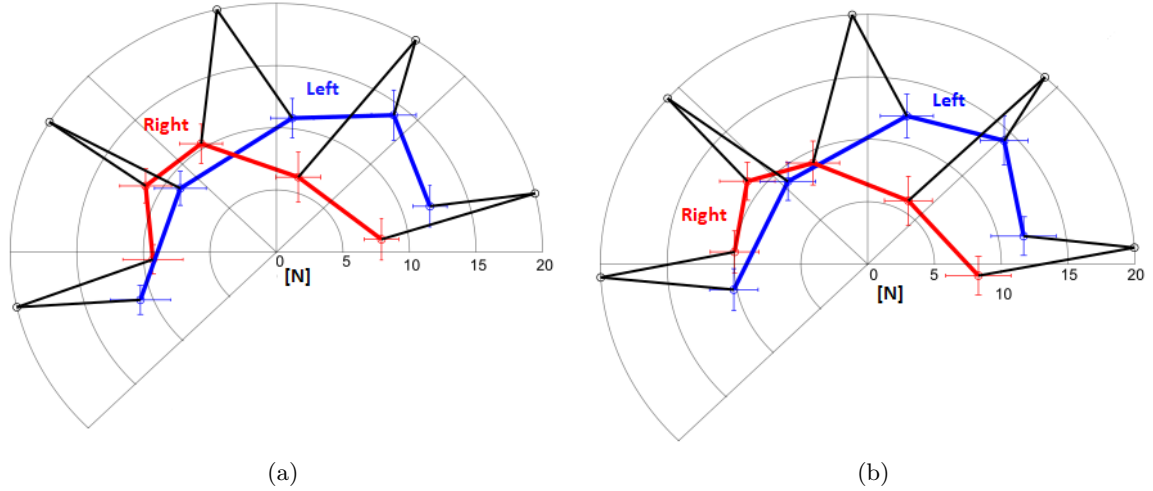


Figure 4.9: Force Production Map for our second group of subjects after the right visuomotor rotation and 3cm (a) or 5cm (b) cursor jump towards the left. Blue stands for the left hand, while red represents the right hand and black lines show the different virtual targets. Since we used a bimanual task, each virtual target corresponds to a sum of force contribution of the right and left hand.

And we can see in figure 4.8 that, for cursor jumps taking place in the same direction as the visuomotor rotation, the only notable difference is due to the change of position of the virtual targets. The global shape of the figure remains the same, and the amplitude of force production distributed across the two hands to reach each target is almost the same as it was after the visuomotor rotation only, in figure 4.7 b.

On the other hand, as it was already the case for the left visuomotor rotation, we can notice that

the effects of cursor jumps in the direction opposed to the visuomotor rotation are way more pronounced. Indeed, once again, this condition leads to results very close to the ones found in the initial case, before the introduction of the visuomotor rotation, that can be seen in figure 4.7 a. The left hand recovers more importance in the amount of force produced, with almost 75% of the total force produced to reach the target located at 45° . This leaves thus just a little bit more than 25% of the force to be produced by the right hand, which was not the case for the cursor jumps taking place in the same direction as the visuomotor rotation.

Finally, as it was the case for the left visuomotor rotation, the results obtained for the right visuomotor rotation show that the impact of the amplitude of the cursor jumps is very discreet. The global shapes of the figures for cursor jumps of 3 or 5cm are almost the same. They only undergo some minor changes that are due to the different locations of the virtual targets.

After all this, we once again decided to analyze the evolution in the total amount of force produced by each hand for the different conditions that we used during our whole experiment to find out if one hand is specifically preferred or not. To do so, we made the same analysis that can be found in figure 4.6. But this time, since we want to discover the effect of the visuomotor rotation towards the right, we adapted it for our second group of subjects. Results can be found in figure 4.10 just below.

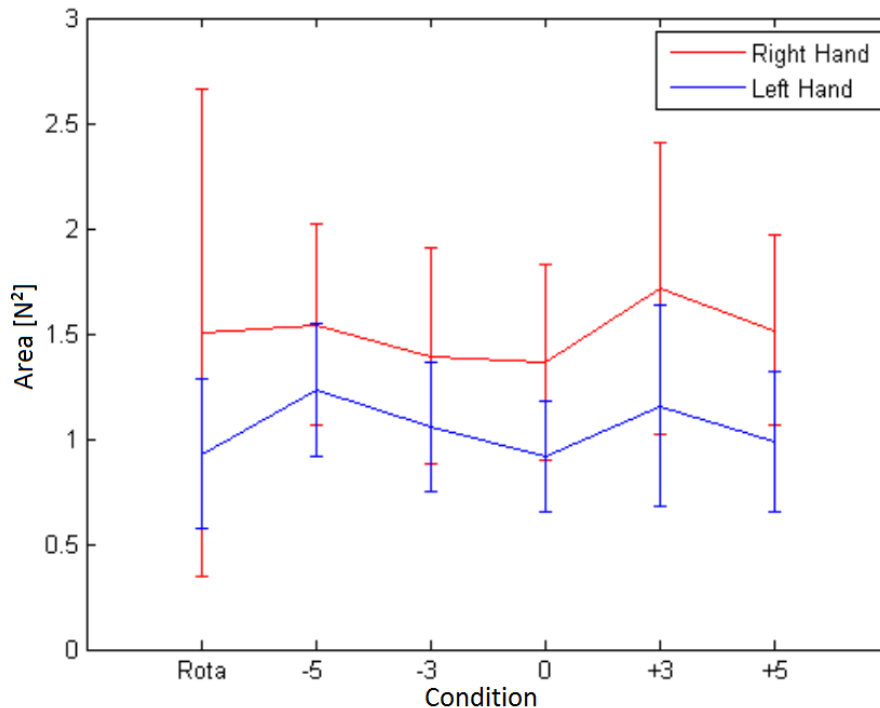


Figure 4.10: Mean and standard deviation of the areas of the left (in blue) and right (in red) hands of the FPM found for our second group of subjects, normalized by the values obtained for the area of the initial condition, for different conditions of the experiment. Rota stands for the end of the second block, when the visuomotor rotation has just been fixed to 30° towards the right, while the five other conditions represent the different amplitudes of cursor jumps that can be faced during the third block of our experimental task ("- is for the cursor jumps towards the left, "+" is towards the right).

And this time, we can notice that results are reversed from the one obtained for the left visuomotor rotation. Indeed, we can see that the right visuomotor rotation brings more importance to the right hand, while the contribution of the left hand remains almost the same as it was when no visuomotor rotation was applied.

Likewise, for the cursor jumps in the same direction than the visuomotor rotation, both hands are more used in an almost similar way. This was also the case for the right visuomotor rotation. Moreover, the contribution of both hands is also higher for cursor jumps opposed to the direction of the visuomotor rotation, even if in this case, the left hand shows a small preference compared to the right hand. Finally, once again, cursor jumps of 0cm give results almost similar to the case with only the visuomotor rotation.

4.4 Evolution of the forces trajectory

Now, we have a good idea of the impact that the visuomotor rotation has on the distribution of forces across our two hands to reach the different targets. But, the different FPMs only give us information about the end of the movement, and not about what happens during the movement itself. We decided thus to focus our next analysis on the whole movement in order to see if there are differences between the left and right hand. More precisely, we wanted to see if one hand corrects the trajectory of the cursor more than the other one, and if this correction varies for each target or not.

To do so, we decided to look at the evolution of the angle of the force trajectory for each hand. But, before going further, we have to define what we mean by "the angle of the force trajectory". In figure 4.11 a, you can see the trajectory of the force of both hands produced by a subject for a single trial. And what we decided to define as the "angle of this trajectory" is simply the angle of the slope between the starting point of the trajectory and any other point of the trajectory. Figure 4.11 b represents the evolution of this angle for the trajectory of the figure 4.11 a during the movement.

Then, in order to find the starting point, we have to differentiate the noise in the forces applied by the subject and the forces applied with the goal of reaching the target. To find it, we used a threshold of 1.7 N above the mean of the global force produced.

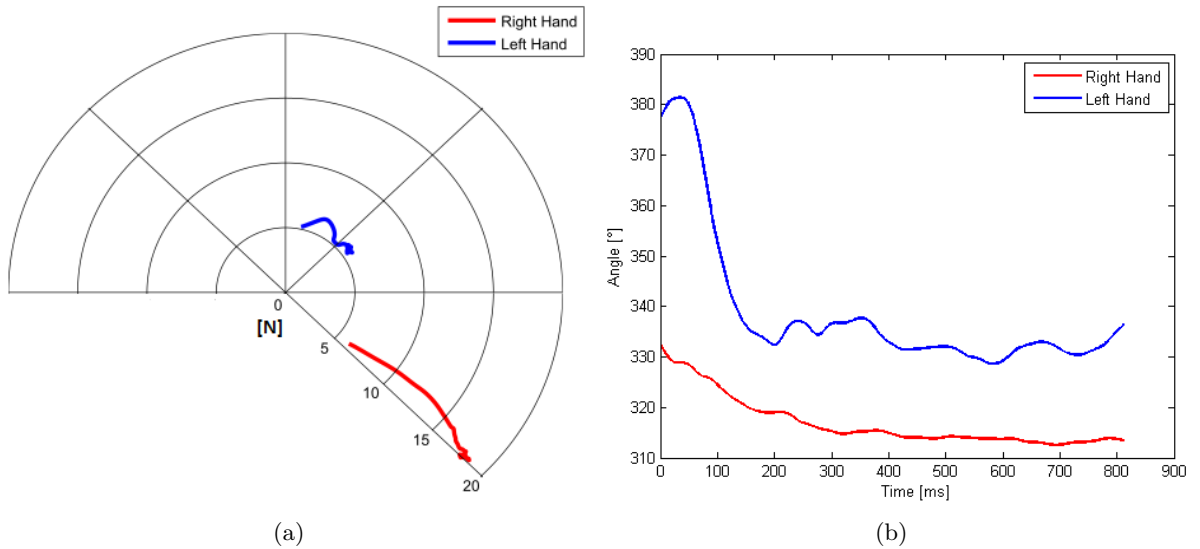


Figure 4.11: Force trajectory (a) and time evolution of the angle of that force trajectory (b) for a single trial and for the visual target at 0° when the visuomotor rotation is anchored at 30 degree to the left. Blue curves represents the left hand, red curves is for the right hand.

So, to get precise and usable results, we decided to extract a representative parameter from this variable. We chose to measure the amplitude between the maximum and minimum value of

the evolution of the angle. Figure 4.12 shows how our measurements were realized. We decided to focus on this specific parameter because we think that it is suitable for finding which hand corrects the trajectory of the cursor since it reveals a change in the direction of the force produced by the subject. Indeed, if the amplitude is low for one hand, it means that this hand has a quite straight-lined trajectory while, on the opposite, if the amplitude is high, it means that the hand makes a correction in its own direction.

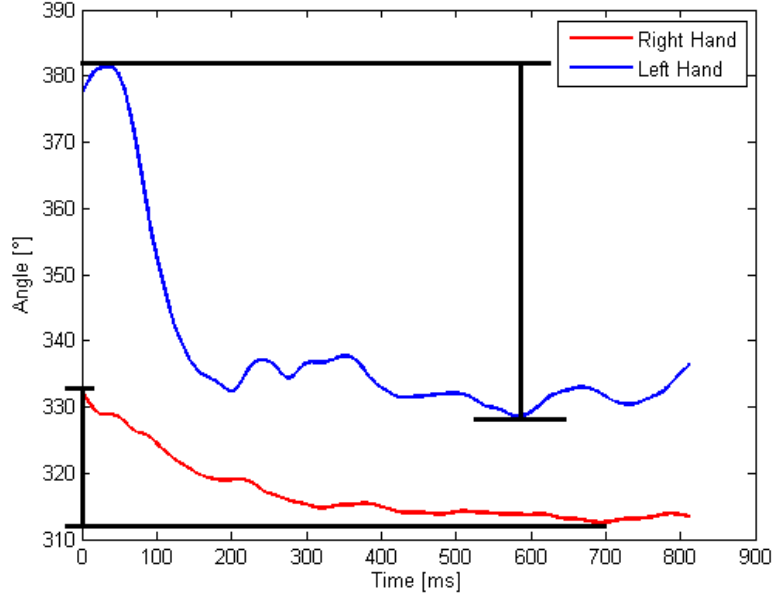


Figure 4.12: Time evolution of the amplitude of the angle coming from the force trajectory. The blue curve represents the left hand, and the red curve is for the right hand.

Figure 4.13 shows the mean and standard deviation of the amplitude of the angle for both hands for our first group of subjects, which got the visuomotor rotation towards the left. So, for each target, we computed the mean of every successful trial when the visuomotor rotation is anchored (at the end of block 2).

We can clearly see that the target affects the hand with the highest amplitude. But, in order to be sure that the difference between the hands was real, we decided to do two different statistical analysis. First, we have done a two-way repeated measures ANOVA. We used that type of ANOVA because we wanted to see if there exists an interaction between the different targets and the hands. And from this ANOVA, we found out a significant interaction between those two factors ($p\text{-value} = 5.0748 * 10^{-7} < 0.05$). After that, we made ttests to compare if the mean of the amplitude of the angle of the left and right hand are different for each target. Each ttest will thus compare the ten values of each hand, and the obtained results will be considered as significant if the p-value is once again lower than the usual threshold. Table 4.1 shows the results of these ttests. As you can see, except for one value, all the test are conclusive. Similar results have been found for the other group of subjects, which got the visuomotor rotation in the other direction. The figure showing it, as well as the table containing the associated ttest values can be found in the Appendix F.

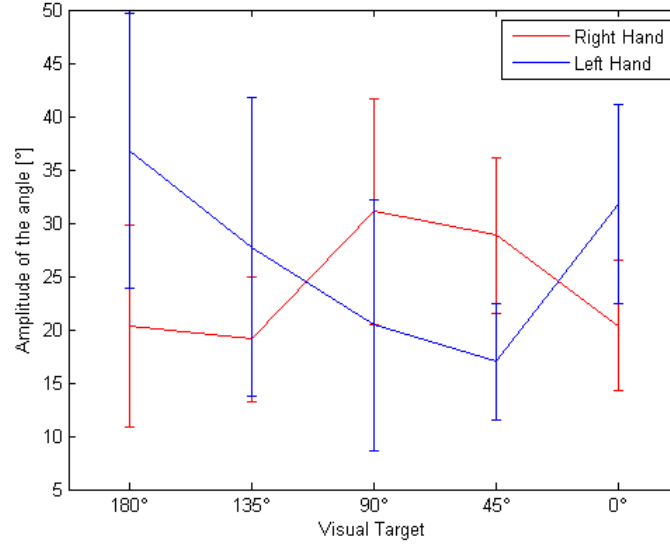


Figure 4.13: Mean and Standard deviation of the amplitude of the angle for every target for the left visuomotor rotation

Visual Target	180°	135°	90°	45°	0°
pvalue	0.0044	0.0899	0.0477	0.0007	0.0048

Table 4.1: p-values of the ttests comparing the mean of the amplitude of the angle for the left and right hands for every target for the left visuomotor rotation

After that, we tried to see if the difference between the targets is already present when the visuomotor rotation is being gradually integrated (during block 2.1). Figure 4.14 shows this evolution for the period 0° to 10°, 10° to 20° and 20° to 30°. And, even if this is not so obvious, we retrieved the same pattern as before. Indeed, the left hand (blue lines) seems to have a higher amplitude for the targets at 0° and 180° while the right hand has a higher amplitude for the target at 45°. This indicates that the difference between the targets is present from the beginning of the induction of the visuomotor rotation.

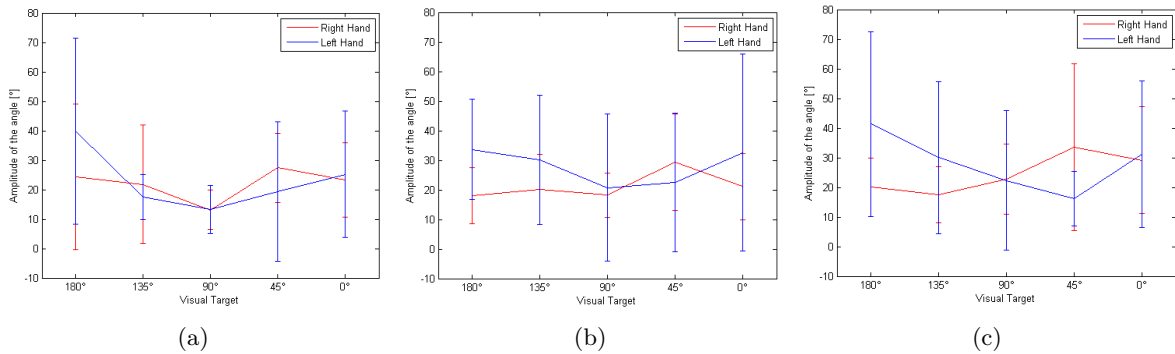


Figure 4.14: Mean and Standard deviation of the amplitude of the angle for every target during the integration of the left visuomotor rotation, between 0° to 10° (a), 10° to 20° (b) and 20° to 30° (c)

Finally, we have done the same analysis for the last block of our experience, the one with the cursor jumps, once again in order to find out if there are differences between hands for the online corrections.

Since we have five different conditions per target, we decided to build a figure for each target. So, this way, we can have the different types of cursor jump as horizontal conditions in our figures, which is more interesting in this case.

And as it is shown in figure 4.15, we can see that there is a pronounced difference in the correction according to the type of cursor jump, but also the target to reach. For the target visually located at 0 degree, we can notice that, in this case of a left visuomotor rotation, the left hand goes through a higher change in its forces trajectory than the right hand, whatever the amplitude and direction of the cursor jump. Nevertheless, a similar pattern can also be distinguished : the change is maximal for both hands for the cursor jumps with the highest amplitude and in the same direction as the visuomotor rotation. The exact same things can be observed for the visual target located at 90 degree, except that it is now the right hand that undergoes the highest changes in its forces trajectory. Note that the same kind of pattern can be observed for all the targets and both directions of the visuomotor rotation. The other figures, showing the results for the 8 remaining conditions, have been placed in the Appendix G.

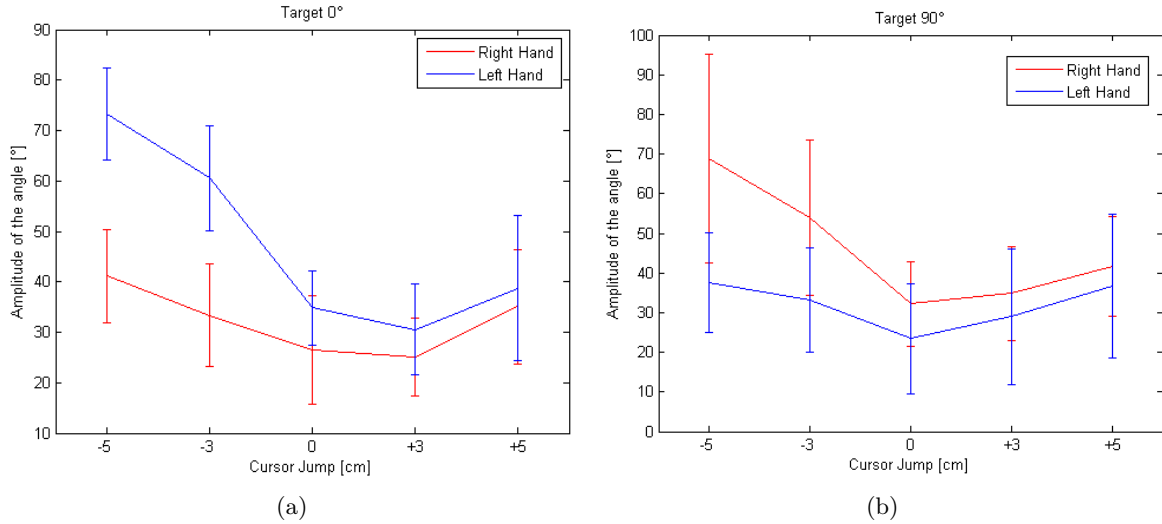


Figure 4.15: Mean and Standard deviation of the amplitude of the angle for our first group of subjects (visuomotor rotation towards the left) and every type of cursor jumps ("- is for the cursor jumps towards the left, "+" is towards the right), for the visual target located at 0° (a) and 90° (b)

4.5 Evolution of the cursor trajectory with the progressive visuomotor rotation

After all these analysis, we still have no idea of the precise effect played by the visuomotor rotation on the trajectory of the movement of the subjects. Yet, this could have a real interest since we ignore the strategy favored by the subjects to correct this hidden perturbation and still reach the desired target. Naturally, the optimal trajectory would be a straight line from the starting point to the target. But we estimate that the progressive introduction of the visuomotor rotation will be a perturbation strong enough to unable the subjects to keep a trajectory close to the optimal one.

So, in order to find out the effect of the introduction of the visuomotor rotation on the trajectory, the speed with which our subjects unconsciously discover this hidden perturbation and the way they adapt their whole movement to correct it, we analyzed the mean trajectory at different moments of the experiment. This can be found in figure 4.16, which illustrates this for our second group of subjects, who underwent the right visuomotor rotation.

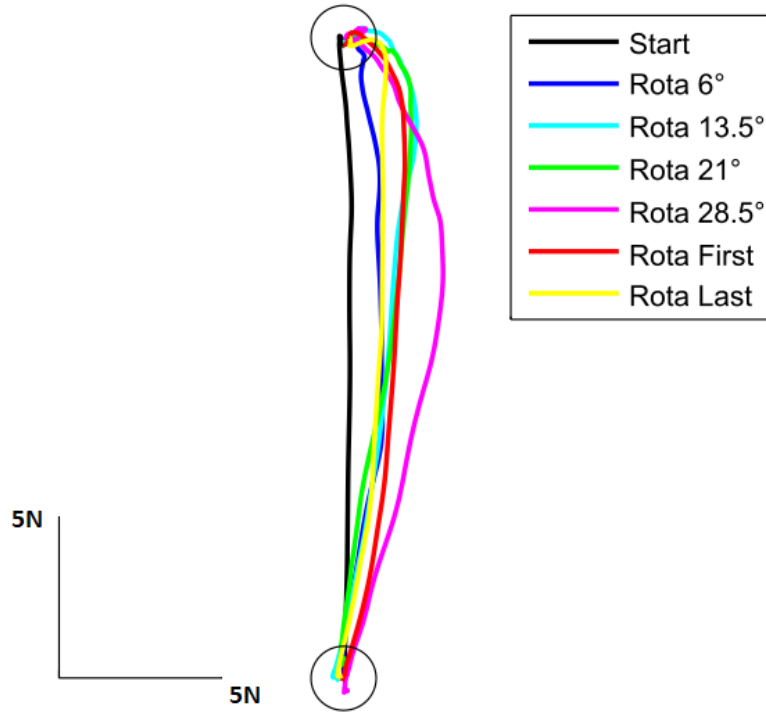


Figure 4.16: Cursor trajectory for the upper target at different moments during the experiment, representing different conditions. Black curve is representing the mean trajectory for the 16 trials towards this upper target for our second group of subjects during the first block, without any perturbation. Blue, cyan, green and pink curves are the mean trajectory of the single trial for all the subjects of the second group located at different specific amplitudes of the progressive visuomotor rotation towards the right, respectively 6° , 13.5° , 21° and 28.5° . Red and yellow curves are representing the mean trajectory for the first half and last half of trials towards this upper target for our second group of subjects when the right visuomotor rotation is fixed.

In this figure, we can see that, first of all, the black curve, which represents the initial condition of the experiment, is almost a straight line between our two points. So, it means that the subjects are nearly able to follow the optimal trajectory for unperturbed movements. But we can also notice that it completely changes as soon as the visuomotor rotation is progressively introduced. Indeed, the dark blue line, which illustrates the cursor trajectory after only 6 degree of visuomotor rotation, proves that this rather small perturbation already impacts significantly our movement. The cursor seems to be strongly deflected at the beginning of the trial, and the trajectory starts to be corrected around the middle of the reaching movement. Thanks to the cyan and green curves, we can see that this pattern is not respected all along the gradual increase of the visuomotor rotation. Indeed, these two curves, which stand for the cursor trajectory after respectively 13.5 and 21 degree of the visuomotor rotation, are almost the same. Moreover, they are also different from the previous curve. Even if they are deflected from the optimal trajectory at the beginning of the movement, we can see that they both still remain closer to the black curve than the dark blue curve was. But, on the other hand, they keep deflecting for a longer period of time, and correct their trajectory at the end of the movement. The pink curve follows, for its part, another pattern. Strongly deflected since the beginning of

the movement, it is the curve that goes the furthest from the black curve. Even the red and yellow curves, which represent trials with a more advanced degree of visuomotor rotation, start to compensate the wrongly induced trajectory earlier. Finally, we can also notice that the yellow curve is closest from the optimal trajectory than the red curve, while they both represent trials where the visuomotor rotation is fixed to 30 degree. The only difference between those trials is the moment at which they took place during the experiment : red is for the first half of trials in the second part of block 2, when the visuomotor rotation is fixed, while yellow is the last half of them.

Furthermore, similar results can be found for the other group of subjects, for who the visuomotor rotation was towards the left. Figure illustrating this has been placed in the Appendix H.

CHAPTER 5

DISCUSSION

In this section, we will use and summarize all the analysis and results obtained in the previous section to answer our question "*How is responsibility assigned in a redundant system during a bimanual task ?*" and report all the interesting things that we found in that field of research.

5.1 Adaptation to the visuomotor rotation

In the last analysis realized in the previous section (figure 4.16), we have seen that the cursor movement achieved under similar conditions could be different. Indeed, the movement performed by the subject just after the anchoring of the visuomotor rotation is further of the optimal trajectory than the movement realized a few tens of trials later. Even if we do not have any evidence to confirm it, we estimate that this is due to the motor adaptation to the unknowingly perturbed movement. Indeed, the phenomena of adaptation is something that has already been studied a lot, under different approaches [25, 26, 27]. And those studies highlighted that adaptation is more than a simple error cancellation process. It is rather a process in which the nervous system learns to predict the effects of a new environment, and then tries to maximize the performances of desired movements into that environment [25, 26].

And this can also be found into our work. Indeed, we saw that for unperturbed trials, the cursor trajectory is almost similar to a straight line between the starting point and the target. We can thus expect that this straight line corresponds to the optimal trajectory in that first case [6]. Then, when we progressively introduced the hidden visuomotor rotation, we changed the environment of the subject, even if he is not aware of it. So, his cursor trajectory will progressively be moved away from the optimal trajectory. It will reach a maximal error around the end of the progressive visuomotor rotation. This makes us think that adaptation to an unconscious perturbation like the visuomotor rotation is not a process fast enough to restore a nearly optimal movement right away. And this is consistent with what has been found in previous studies that showed that adaptation is made through practice in the novel environment, and that rotation learning consolidates over time [27]. It seems like we need time to be able to predict accurately the new sensory consequences of motor commands by adapting our internal model [26].

And this can be confirmed by the cursor trajectories found when the visuomotor rotation was fixed to 30 degree. Even if the subjects had to perform that kind of trial right after the progressive introduction of the visuomotor rotation, without any break between them, we found a remarkable difference in their movements. Indeed, we saw in figure 4.16 that the cursor trajectory of the trials with visuomotor rotation fixed to 30 degree returns progressively to the initial

trajectory. This proves that the subjects are able to learn and adapt to this novel environment if we let them enough time. This allows them to plan a better movement in order to minimize motor cost, corresponding to movements closer to the straight line between the two points.

Finally, since the results concerning the cursor trajectory for both directions of the visuomotor rotation are comparable, we can hypothesize that the direction of the visuomotor rotation has no effect on the process of adaptation.

5.2 Influence of the direction of the visuomotor rotation

During the analysis of the different Force Production Maps in the previous section (see figures 4.3 to 4.10), we showed that the effects of the visuomotor rotation are clearly different according to its direction. Nevertheless, some similarities can still be highlighted.

First of all, whatever the direction of visuomotor rotation, a higher importance in the force distribution is given to the hand in the same direction as the visuomotor rotation. So, the left hand is favored during the left visuomotor rotation, while the right hand acquires more importance during the right visuomotor rotation. Furthermore, different patterns of force distribution are used after the introduction of the visuomotor rotation. But these new patterns still follow some rules that could already be found in the distribution of force production for the basic trials, before the visuomotor rotation. Indeed, whatever the direction of the visuomotor rotation, the hand favored by the subjects is the hand that is the closest to its preferential direction of force production. And due to the new virtual targets induced by the visuomotor rotation, this leads to a new pattern of force distribution : for the extreme targets (at 0 and 180 degree), the hand opposed to the direction of the visuomotor rotation is preferred, while for the other targets (at 45, 90 and 135 degree), it is the hand in the same direction as the visuomotor rotation that is favored.

This effect, already present for the initial condition, tends to prove that biomechanical constraints have a huge influence on the way we deal with a visuomotor rotation. Nevertheless, an important difference with what has been found in that field by David Cordova has to be mentioned.

Indeed, during his research, it has notably been shown that, for the joint configuration that we used during our experiment, these preferential directions are located around 45° for the left hand and 140° for the right hand. This has been confirmed in the beginning of our analysis (block 1, see figure 4.2). But, we can also notice that, when a visuomotor rotation is present, it is not the case anymore. The preferential directions seem to be moved in the same direction than the induced visuomotor rotation. This effect brings us to new preferential directions located around 60° for the left visuomotor rotation and 130° for the right visuomotor rotation. This can be seen on figures 4.3 and 4.7.

Moreover, the FPM produced for the different cursor jumps that we used during our third and last block of the experiment are showing that cursor jumps also seem to move the preferential direction. Indeed, we saw that the way forces are distributed across hands is very similar when the subjects are facing the visuomotor rotation alone and when they have to deal with the visuomotor rotation as well as cursor jumps in the same direction. The only notable difference is that cursor jumps tend to bring the preferential direction back to its initial location. And this effect can be found as well for cursor jumps in the same direction than the visuomotor rotation (see figures 4.4 and 4.8) as for cursor jumps in the direction opposed to the visuomotor rotation (see figures 4.5 and 4.9). Indeed, in all those figures, we can notice that the preferential directions found match way better with the initial ones.

On the other hand, we also highlighted the fact that cursor jumps in the direction opposed to the direction of the visuomotor rotation are giving force distributions relatively close to the initial case. Yet, in this case, cursor jumps with an amplitude of 5cm bring the virtual positions of the targets back to locations really close to the visual targets. And previous studies have shown that both feedback control and adaptation, which are the regulators of our ability to realize perturbed movements, change optimally with task goals [3]. So, in this specific case, we believe that the central nervous system identifies the cursor jump as a correction for the perturbation introduced by the visuomotor rotation. Then, since the error is already largely corrected, it estimates that the final task goal of this movement is almost similar to the task goal of the initial movement. We think thus that cursor jumps opposed to the direction of the visuomotor rotation sort of cancel the effects introduced by this visuomotor rotation to the subject. At least, that would explain the results that we found : a same force distribution for a same task goal.

Finally, the analysis realized on the evolution of the total amount of force produced by each hand, represented by the area of the FPM (see figures 4.6 and 4.10), through the different conditions of our experiment was also very interesting. Indeed, it allowed us to discover that, whatever the direction of the visuomotor rotation used, the global contribution of the hand in the same direction as the visuomotor rotation is increased compared to the initial condition (without any visuomotor rotation). In other words, the global contribution of the left hand in the force production will be increased after the left visuomotor rotation, while the visuomotor rotation towards the other direction shows the same effect on the other hand. This is due to the fact that the virtual targets are located closer to the preferential direction of the left hand for the left visuomotor rotation, and inversely for the right visuomotor rotation. Moreover, this pattern remains globally the same for the different amplitudes of cursor jumps. This shows that, for the distribution of force production, we do not rely on handedness but on biomechanical constraints.

5.3 Amplitude of the correction

Our previous analysis tend to show that biomechanics play a more important role than handedness for the corrections of the visuomotor rotation during our bimanual task. We thus decided to analyze the amplitude of the angle during the movement to see which hand corrects the trajectory and to see if it confirms our hypothesis.

First of all, figure 4.13 shows that there is a difference between the correction made by each hand when the subject underwent the visuomotor rotation to the left. Moreover, the hand that corrects the most varies according to the target, which, by extension, also means according to the direction of the movement. And, thanks to statistical analysis, we have been able to prove that there is a statistically significant difference between the contribution of both hands in this correction for each target except one (see table 4.1).

Now that we know that the difference is not due to chance, we can try to interpret it according to biomechanics and handedness. The left hand corrects more for the visual target at 0 and 180°, so when the direction of the virtual target is close to the preferential direction of the right hand. While, on the other hand, the right hand corrects more for the visual target at 45° and 90°, when the direction of the virtual target is close to the preferential direction of the left hand. The only target for which the difference between the hands is not statistically significant is when the virtual target is close to 90° (visual target at 135° and virtual target at 105°). So, when the target is located in between the preferential directions of the two hands.

And the same effect can be highlighted for our second group of subjects, who had the visuomotor to the right. Indeed, for the target close to the preferential direction of the right hand, the left hand corrects significantly more, and vice versa when we changes the preferential direction. And,

for the virtual target located at 75° , and so once again close to 90° and the switch in preferential direction, no significant difference between the hands can be found.

After that, we turned our attention to the last block of the experiment to find out how the different cursor jumps impact this correction. This has been shown in the two figures 4.15 a and b, that must be interpreted separately. Indeed, here, each figure shows the effects of all the types of cursor jumps that we used, but for only one target. If we first look at the figure 4.15 a (so for the visual target at 0°), we can see that the effect is clearly different according to the direction of the cursor jump. We estimate that this can be explained by the fact that the cursor jump to the left goes in the same direction that the visuomotor rotation (see figure 4.4), emphasizing its effect, while the cursor jump to the right "counters" the visuomotor rotation (see figure 4.5). The cursor jump to the left forces thus the subject to go further into the preferential direction of the right hand. Moreover, we can also notice that it is the left hand that has the highest amplitude, and that the difference between the amplitude of the two hands increases with the amplitude of the cursor jump in the left direction. On the other hand, for the cursor jumps in the right direction, we can see that the difference in the contribution of the two hands is really small. Indeed, in that case, the virtual target is close to 0° , and thus close to the transition in the preferential direction of the two hands.

Figure 4.15 b shows similar results but with the preferential direction of the left hand since the visual target is this time located at 90° . The cursor jump to the left goes then into the preferential direction of the left hand, and the right hand corrects thus more the direction of the movement. Finally, both hands correct almost equally when the movement is perturbed by cursor jumps in the right direction because, in that case, the virtual target to reach is close to the switch in the preferential direction of the hands.

5.4 How is responsibility assigned in a redundant system during a bimanual task ?

Now that we made all this work, we can answer the question that interests us. First of all, we proved that the first hypothesis that we made when we started our work (see Aim of the work) is wrong. Indeed, we showed that the global contribution of force production is independent of handedness.

On the other hand, we have also been able to show that, for our bimanual force task perturbed by the introduction of a progressive visuomotor rotation, subjects changed their force distribution based on the preferential directions of their hands. So, responses to the visuomotor rotation are made by a combined effect of both hands according to the direction of the movement instead of handedness. Moreover, the effects of different cursor jumps on that task were different according to the direction of these cursor jumps, but remained driven by the preferential directions found before.

Furthermore, we have also been able to show that the corrections for this hidden perturbation are mostly realized by the hand which is the less used for the force production. So, once again, this changes according to the direction of the movement in order to respect the preferential directions.

Put together, all this allows us to say that, in a redundant system during a bimanual task, responsibility is assigned according to biomechanics. It seems like our motor system distributes work based on biomechanical constraints, and more specifically the preferential directions of both hands. Since it is the less experienced hand in that direction, and thus the most likely cause, the motor system decides that the hand which is the furthest to its preferential direction is the

source of the error. So, the motor system corrects mostly with that specific hand, leaving the other one, closest to its own preferential direction, mainly concentrate on the force production.

CHAPTER 6

CONCLUSION

Human beings are very complex organisms. Every human is different, as well in their morphology than in their behavior. Thanks to internal models that predict movements coupled to a feedback control allowing to correct for potential errors, human beings are able to perform every day life motor activities in an accurate way. Moreover, due to redundancy, many different combinations of motor commands for the different effectors involved can lead to the success of the task fixed. Nevertheless, in order to achieve a given task, an optimal movement, which will be preferred to the other ones, can be found. And this optimal movement depends on many different parameters, such as the current state of the body, the previous experience of the person, the surrounding environment, ...

So, when the task to realize is simple, and made into a well-known environment, the motor system distributes work across effectors according to what it estimates to be the optimal movement. But, when an error occurs, the motor system faces a problem since it ignores which effector caused it.

Thus, during this work, we decided to analyze the way our motor system assigns responsibility when facing an error induced by a hidden visuomotor rotation during a bimanual task. To do this, we based our approach on previous experiments realized in the same field. So, we used a bimanual force production task in which subjects, restricted to a given joint configuration, were asked to reach a given target with a single cursor that moved according to the direction and amplitude of the forces produced by each hand. Moreover, different conditions were successively used during the experiment. First of all, the movement was unperturbed. Then, a visuomotor rotation was progressively induced until reaching an amplitude of 30 degree. From that moment, the visuomotor rotation remained fixed at that value. Finally, we also added different possible cursor jumps on top of it.

This experiment has been implemented on a robot KINARM, and then realized by 20 right-handed subjects. And the different analysis realized on the obtained results allowed us to show that responsibility is assigned according to biomechanical constraints. Indeed, it is always the closest hand to its preferential direction of force production which is the most used in terms of force production contribution, while the other hand is preferentially used to correct the movement. Finally, we also showed that handedness is not taken into account for the corrections of the induced perturbations. Indeed, no effect specific to handedness has been reported, neither in the distribution of force production and corrections, nor in the adaptation to the visuomotor rotation or in the global contribution of force production.

BIBLIOGRAPHY

- [1] Shadmehr R., *Actuator and Kinematic Redundancy in Biological Motor Control*, Research Notes in Neural Computing, Volume 3, pp 239-254, August 1991
- [2] Vetter P., Flash T. and Wolpert D.M., *Planning movements in a simple redundant task*, Current Biology, Volume 12, pp 488-491, March 2002
- [3] Diedrichsen J., *Optimal task-dependent changes of bimanual feedback control and adaptation*, Current Biology, Volume 17, pp 1675-1679, October 2007
- [4] Nashed J.Y., Crevecoeur F. and Scott S. H., *Influence of the behavioral goal and environmental obstacles on rapid feedback responses*, Journal of Neurophysiology, Volume 108, pp 999-1009, August 2012
- [5] Motor Control, https://en.wikipedia.org/wiki/Motor_control, page viewed on April 11, 2017
- [6] Haith A., Huberdeau D. and Krakauer J., *Hedging your bets : Intermediate movements as optimal behavior in the context of an incomplete decision*, Plos : Computational Biology, Volume 11, March 2015
- [7] Kawato M., *Internal models for motor control and trajectory planning*, Current opinion in neurobiology, Volume 9, pp 718-727, December 1999
- [8] Wolpert D. and Flanagan J. R., *Motor prediction*, Current Biology, Volume 11, pp 729-732, 2001
- [9] Davidson P. and Wolpert D., *Widespread access to predictive models in the motor system : a short review*, Journal of Neural Engineering, Volume 2, pp 313-319, 2005
- [10] Miall R.C. and Wolpert D., *Forward Models for Physiological Motor control*, Neural Networks, Volume 9, pp 1265-1279, 1996
- [11] Konczak J. and Abbruzzese G., *Focal dystonia in musicians : linking motor symptoms to somatosensory dysfunction*, frontiers in Human Neuroscience, June 2013
- [12] Todorov E. and Jordan M.I., *Optimal feedback control as a theory of motor coordination*, Nature Neuroscience, Volume 5, pp 1226-1235, November 2002
- [13] Bimanual coordination, http://www.icn.ucl.ac.uk/motorcontrol/res_bimancoord.htm, page viewed on April 11, 2017

- [14] Hayashi T., Yokoi A., Hirashima M. and Nozaki D., *Visuomotor map determines how visually guided reaching movements are corrected within and across trials*, eNeuro, Volume 3, pp 1-13, June 2016
- [15] Scott S.H., Cluff T., Lowrey C.R. and Takei T., *Feedback control during voluntary motor actions*, Current opinion in neurobiology, Volume 33, pp 85-94, March 2015
- [16] White O. and Diedrichsen W., *Responsibility assignment in redundant systems*, Current Biology, Volume 20, pp 1290-1295, July 2010
- [17] Salimpour Y. and Shadmehr R., *Motor costs and the coordination of the two arms*, Journal of Neuroscience, Volume 34, pp 1806-1818, January 2014
- [18] Salimpour Y., Mari Z.K. and Shadmehr R., *Altering efforts costs in Parkinson's disease with noninvasive cortical stimulation*, Journal of Neuroscience, Volume 35, pp 12287-12302, September 2015
- [19] Cordova Bulens D., Crevecoeur F, Thonnard J-L. and Lefèvre P., *Optimal integration of biomechanics drives distributed control across limbs during bimanual tasks*, 2017
- [20] KINARM End-Point Lab, <http://www.miyuki-net.co.jp/jp/product/researchEquipment/SenseMovement/KinarmEndPoint.shtml>, page viewed on April 12, 2017
- [21] BKIN Technologies : Features of the KINARM, <http://www.bkintechologies.com/bkin-products/kinarm-end-point-lab/>, page viewed on April 12, 2017
- [22] Caplan B. and Mendoza J.E., *Edinburgh Handedness Inventory*, Encyclopedia of Clinical Neuropsychology, Volume 1, p. 928, 2011
- [23] Simulink - Simulation and Model-Based Design, <https://nl.mathworks.com/products/simulink.html>, page viewed on April 24, 2017
- [24] Stateflow - MATLAB and Simulink, <https://nl.mathworks.com/products/stateflow.html>, page viewed on April 24, 2017
- [25] Bastian E.J., *Understanding sensorimotor adaptation and learning for rehabilitation*, Current opinion in neurobiology, Volume 21, pp 628-633, December 2008
- [26] Izawa J., Rane T., Donchin O. and Shadmehr R., *Motor adaptation as a process of reoptimization*, Journal of neuroscience, Volume 12, pp 2883-2891, March 2008
- [27] Krakauer J.W., *Motor learning and consolidation : the case of visuomotor rotation*, Advances in experimental medicine and biology, Volume 629, pp 405-421, April 2009

Appendices

APPENDIX A

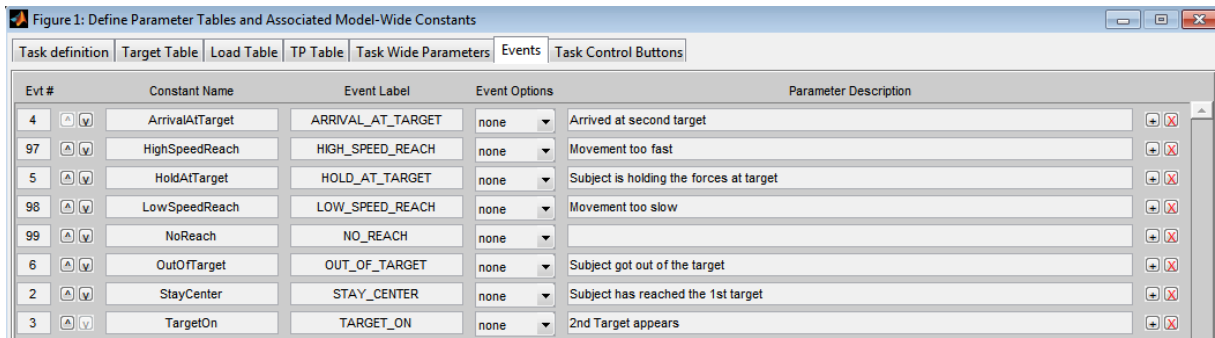
EDINBURGH HANDEDNESS INVENTORY

Edinburgh Handedness Inventory			
Surname _____		Give name _____	
Date of birth _____		Sex _____	
Please indicate your preferences in the use of hands in the following activities by putting + in the appropriate column. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, put ++. If any case you are really indifferent put + in both columns. Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets. Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.			
	Left	Right	
1. Writing			
2. Drawing			
3. Throwing			
4. Scissors			
5. Toothbrush			
6. Knife (without fork)			
7. Spoon			
8. Broom (upper hand)			
9. Striking Match (match)			
10. Opening box (lid)			
i. Which foot do you prefer to kick with?			
ii. Which eye do you use when using only one?			
L.Q.	Leave the spaces blank	DECL	

Figure A.1: Edinburgh Handedness Inventory used to assess the Laterality Quotient of our subjects

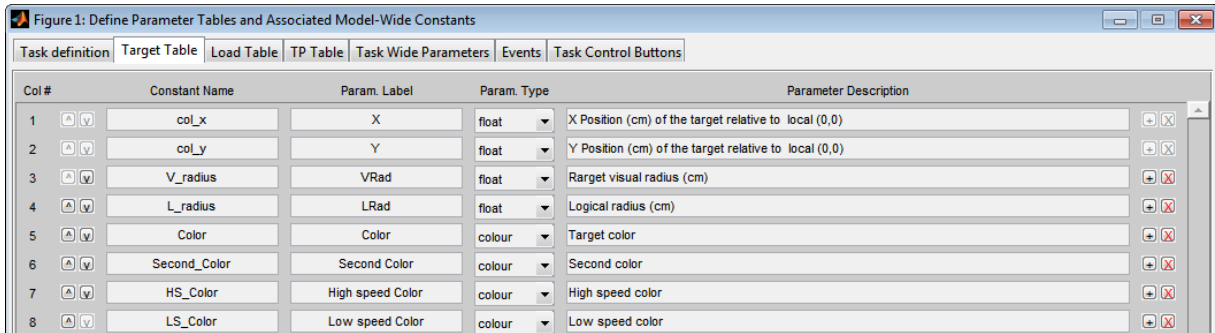
APPENDIX B

PARAMETER TABLE DEFN



Evt #	Constant Name	Event Label	Event Options	Parameter Description
4	ArrivalAtTarget	ARRIVAL_AT_TARGET	none	Arrived at second target
97	HighSpeedReach	HIGH_SPEED_REACH	none	Movement too fast
5	HoldAtTarget	HOLD_AT_TARGET	none	Subject is holding the forces at target
98	LowSpeedReach	LOW_SPEED_REACH	none	Movement too slow
99	NoReach	NO_REACH	none	
6	OutOfTarget	OUT_OF_TARGET	none	Subject got out of the target
2	StayCenter	STAY_CENTER	none	Subject has reached the 1st target
3	TargetOn	TARGET_ON	none	2nd Target appears

Figure B.1: Events table filled into the "Parameter Table Defn"

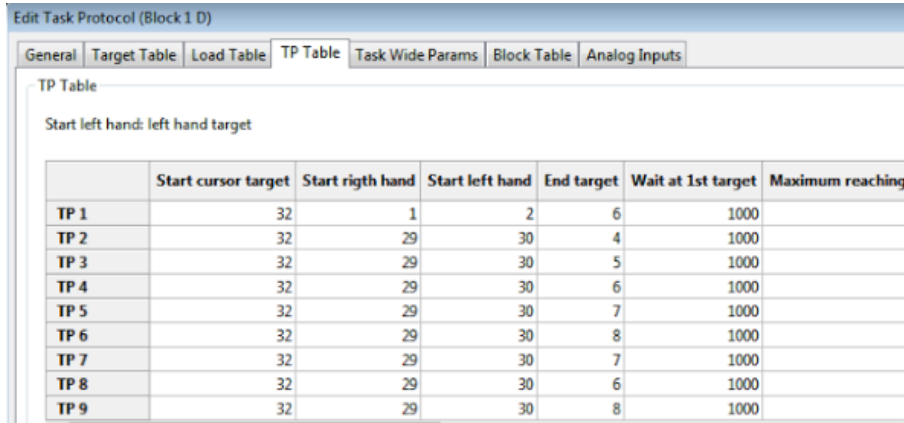


Col #	Constant Name	Param. Label	Param. Type	Parameter Description
1	col_x	X	float	X Position (cm) of the target relative to local (0,0)
2	col_y	Y	float	Y Position (cm) of the target relative to local (0,0)
3	V_radius	VRad	float	Target visual radius (cm)
4	L_radius	LRad	float	Logical radius (cm)
5	Color	Color	colour	Target color
6	Second_Color	Second Color	colour	Second color
7	HS_Color	High speed Color	colour	High speed color
8	LS_Color	Low speed Color	colour	Low speed color

Figure B.2: Target table filled into the "Parameter Table Defn"

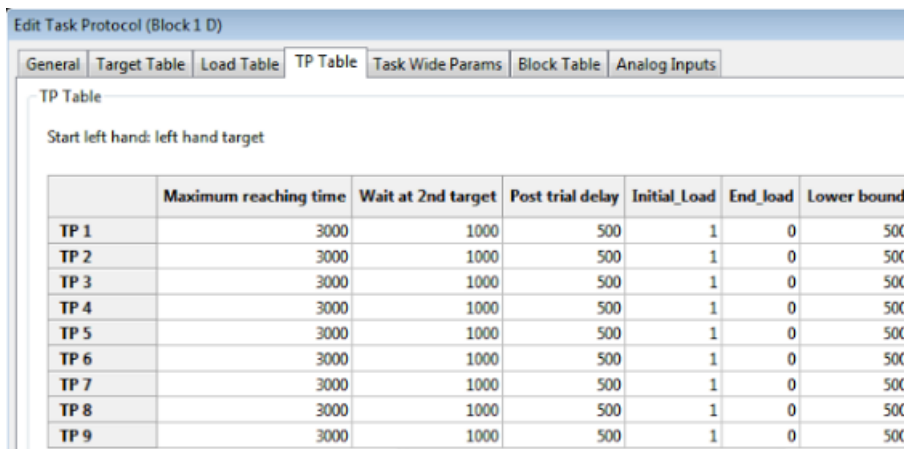
APPENDIX C

EDIT TASK PROTOCOL INTO DEXTERIT-E



	Start cursor target	Start righthand	Start left hand	End target	Wait at 1st target	Maximum reaching
TP 1	32	1	2	6	1000	
TP 2	32	29	30	4	1000	
TP 3	32	29	30	5	1000	
TP 4	32	29	30	6	1000	
TP 5	32	29	30	7	1000	
TP 6	32	29	30	8	1000	
TP 7	32	29	30	7	1000	
TP 8	32	29	30	6	1000	
TP 9	32	29	30	8	1000	

Figure C.1: First part of Dexterit-E's TP Table (Block 1). End target represents the target to reach (4 to 8, at 0° to 180°).



	Maximum reaching time	Wait at 2nd target	Post trial delay	Initial_Load	End_load	Lower bound
TP 1	3000	1000	500	1	0	500
TP 2	3000	1000	500	1	0	500
TP 3	3000	1000	500	1	0	500
TP 4	3000	1000	500	1	0	500
TP 5	3000	1000	500	1	0	500
TP 6	3000	1000	500	1	0	500
TP 7	3000	1000	500	1	0	500
TP 8	3000	1000	500	1	0	500
TP 9	3000	1000	500	1	0	500

Figure C.2: Second part of Dexterit-E's TP Table (Block 1). Different constants are defined here, such as the maximum time to reach the random target before the trial ends by itself, and the time between two trials (= Post trial delay).

Edit Task Protocol (Block 1 D)									
General Target Table Load Table TP Table Task Wide Params Block Table Analog Inputs									
TP Table									
Start left hand: left hand target									
	J target	Post trial delay	Initial Load	End load	Lower bound	Upper bound	Bad Reach	Jump	Partie
TP 1	1000	500	1	0	500	800	1000	0.000	0.000
TP 2	1000	500	1	0	500	800	1000	0.000	0.000
TP 3	1000	500	1	0	500	800	1000	0.000	0.000
TP 4	1000	500	1	0	500	800	1000	0.000	0.000
TP 5	1000	500	1	0	500	800	1000	0.000	0.000
TP 6	1000	500	1	0	500	800	1000	0.000	0.000
TP 7	1000	500	1	0	500	800	1000	0.000	0.000
TP 8	1000	500	1	0	500	800	1000	0.000	0.000
TP 9	1000	500	1	0	500	800	1000	0.000	0.000

Figure C.3: Third part of Dexterit-E's TP Table (Block 1). Here, we can find the allotted time for a successful trial (between the Lower bound and Upper bound). Moreover, we can see that, for this block, cursor jumps are set to 0cm (Jump = 0), and the visuomotor rotation is not yet introduced (Partie = 0).

Edit Task Protocol (Block 1 D)					
General Target Table Load Table TP Table Task Wide Params Block Table Analog Inputs					
Block Table					
TP List: List of trial protocols to include in the block.					
	TP List	List Reps	Catch TP List	Randomized	Block Reps
Block 1	1	1		☐	1
Block 2	2,3,4,5,6	16		☒	1
Block 3		0		☐	0
Block 4		0		☐	0
Block 5		0		☐	0
Block 6		0		☐	0
Block 7		0		☐	0
Block 8		0		☐	0
Block 9		0		☐	0
Block 10		0		☐	0

Figure C.4: Dexterit-E's Block Table (Block 1). We can notice that this first block is only made of one first trial used to launch the experiment, and then of 16 random repetitions of the basic trial towards one of the 5 possible targets.

APPENDIX D

SUCCESS RATE

Subject	Start (/80)	Rota (/140)	Jump1 (/75)	J2 (/75)	J3 (/50)	J4 (/50)	Total (/470)
1	63	99	62	66	45	46	381 (= 81%)
2	59	112	59	65	45	39	379 (= 80.6%)
3	69	116	58	62	48	50	403 (= 85.7%)
4	66	119	64	66	44	48	407 (= 86.6%)
5	71	116	64	67	49	48	415 (= 88.3%)
6	74	105	54	64	43	40	380 (= 80.8%)
7	69	126	56	66	47	47	411 (= 87.4%)
8	64	106	61	68	40	39	378 (= 80.4%)
9	70	126	63	71	49	48	427 (= 90.9%)
10	53	95	57	69	46	44	364 (= 77.4%)
11	58	107	68	68	42	46	389 (= 82.8%)
12	53	80	51	56	42	38	320 (= 68%)
13	39	80	61	58	46	41	325 (= 69.2%)
14	73	131	66	75	50	48	443 (= 94.3%)
15	63	107	62	64	44	43	383 (= 81.5%)
16	68	128	58	70	48	44	416 (= 88.5%)
17	71	123	62	74	50	48	428 (= 91.1%)
18	71	118	69	71	43	48	420 (= 89.4%)
19	71	108	62	72	47	47	407 (= 86.6%)
20	59	97	65	69	41	44	375 (= 79.8%)
Mean	64	110	61	67	46	45	393 (= 83.5%)

Table D.1: Success rate of the experiment for all subjects and all blocks. Best results for each block are in green, worst results are in red. As a reminder, a trial is defined as successful when the subject reached the target within the allotted time, which means between 500 and 800ms for blocks 1 and 2 (called Start and Rota), and between 500 and 1000ms for the last block (called Jump and separated by small breaks into 4 parts).

APPENDIX E

FORCE PRODUCTION MAP FOR CURSOR JUMPS OF 0CM

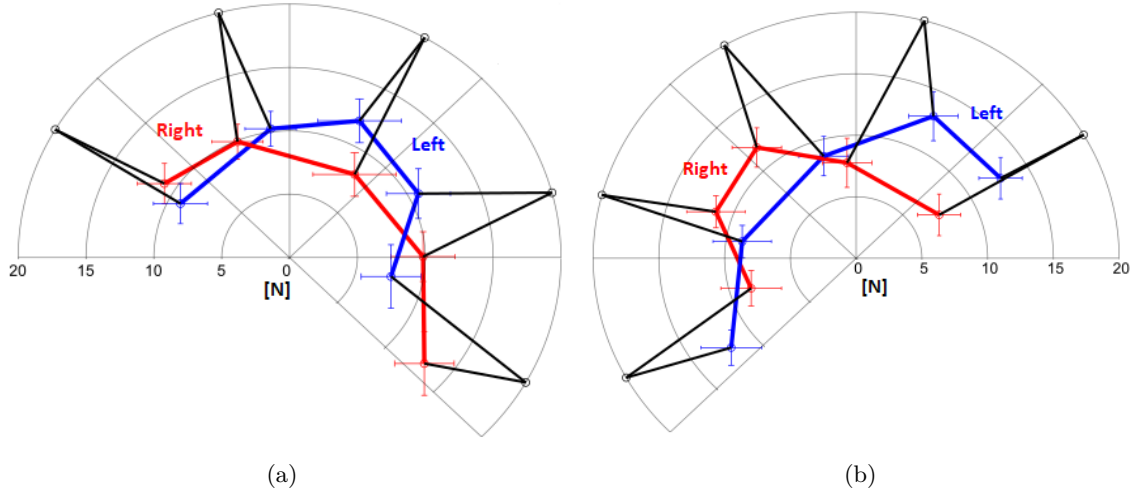


Figure E.1: Force Production Map for our first group of subjects after the left visuomotor rotation and 0cm cursor jump (a) and for our second group of subjects after the right visuomotor rotation and 0cm cursor jump (b). This condition is thus comparable to the one with only the visuomotor rotation induced and no cursor jump, but happens later in the experiment. Blue stands for the left hand, while red represents the right hand and black lines show the different virtual targets. Since we used a bimanual task, each virtual target corresponds to a sum of force contribution of the right and left hand.

APPENDIX F

AMPLITUDE OF THE ANGLE IN THE FORCES TRAJECTORY

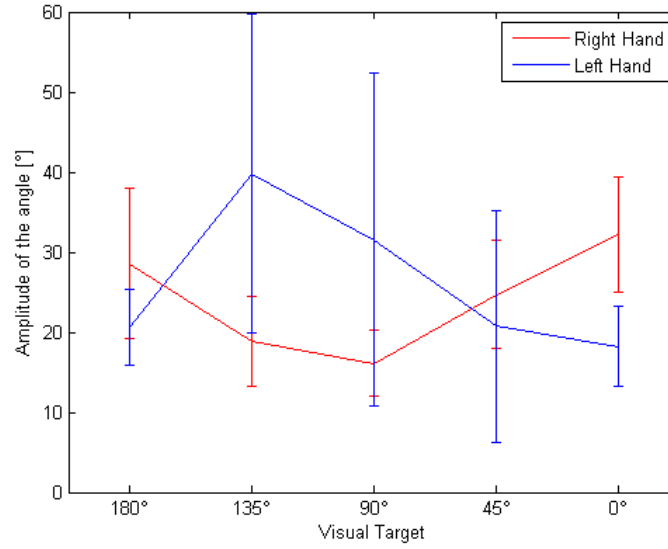


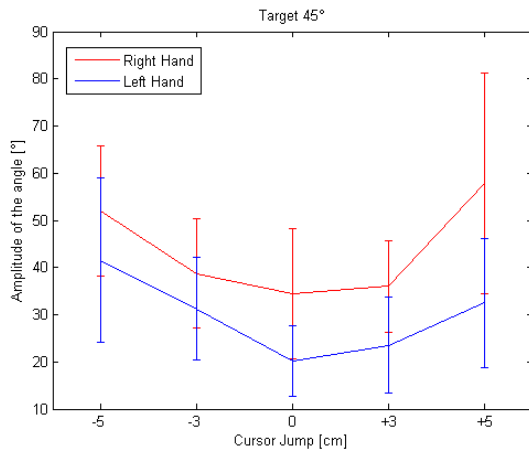
Figure F.1: Mean and Standard deviation of the amplitude of the angle for every target for the right visuomotor rotation

Visual Target	180°	135°	90°	45°	0°
pvalue	0.0272	0.0048	0.0329	0.4460	0.0001

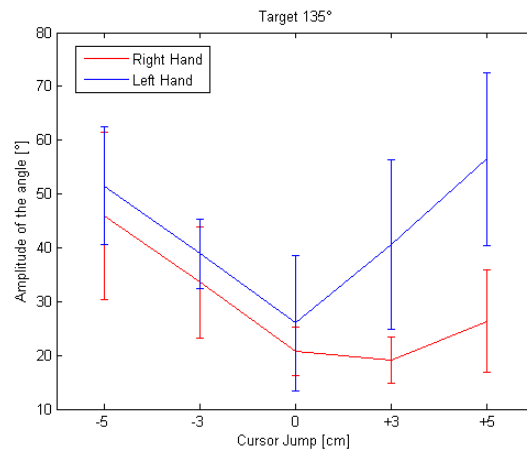
Table F.1: p-values of the ttests comparing the mean of the amplitude of the angle for the left and right hands for every target for the right visuomotor rotation

APPENDIX G

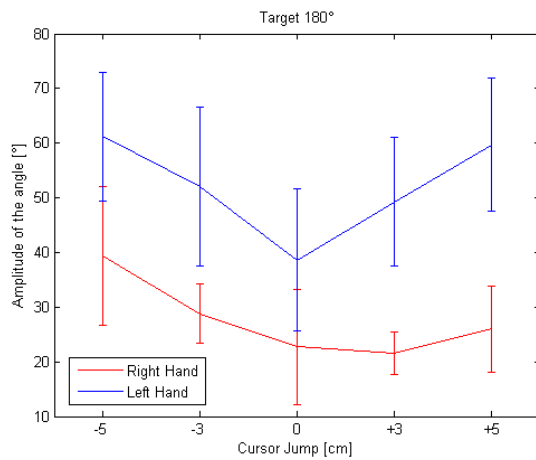
AMPLITUDE OF THE ANGLE IN THE FORCES TRAJECTORY FOR THE CURSOR JUMPS



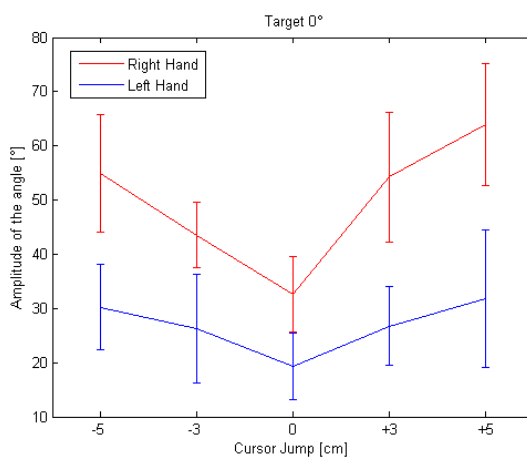
(a)



(b)



(c)



(d)

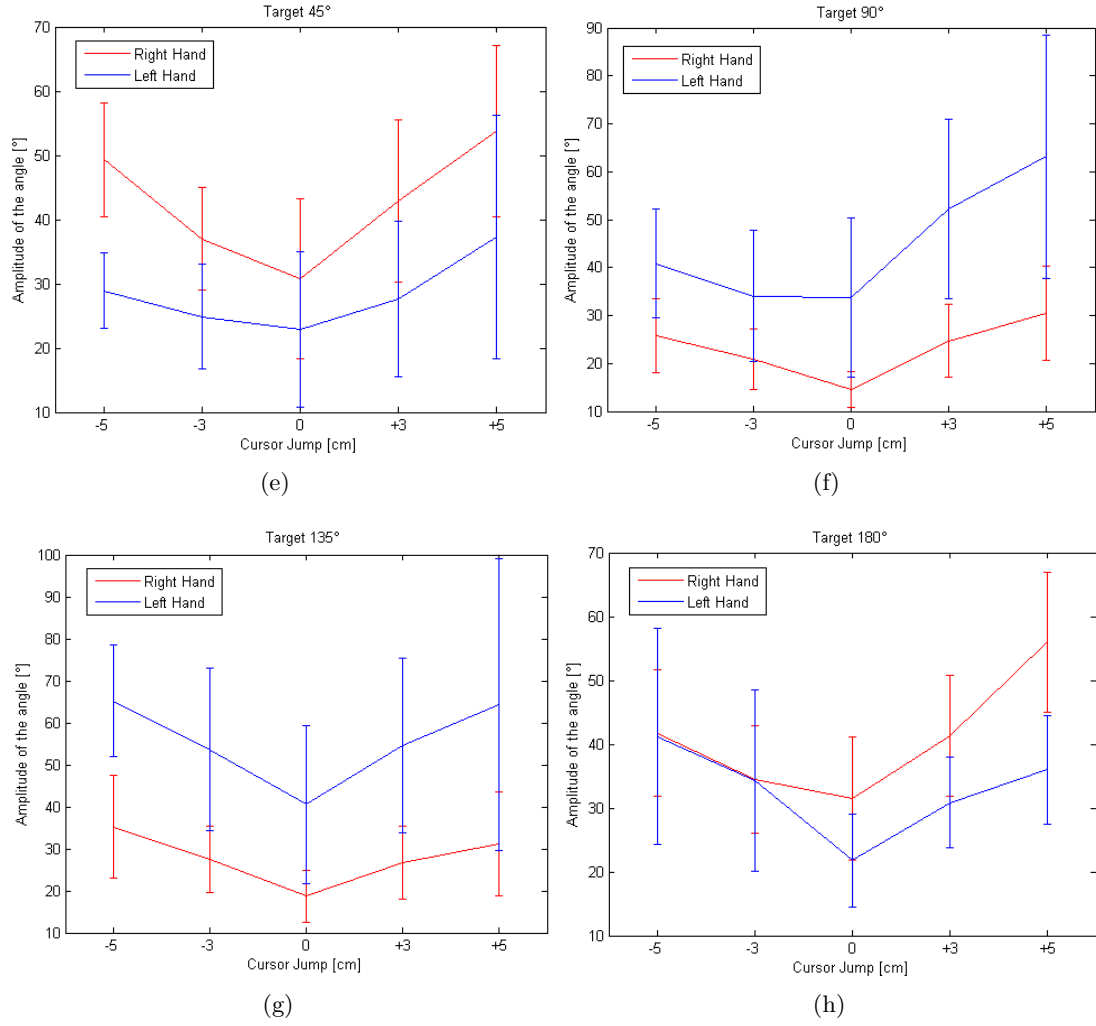


Figure G.1: Mean and Standard deviation of the amplitude of the angle for every type of cursor jumps ("- is for the cursor jumps towards the left, "+" is towards the right). Figures (a), (b) and (c) represent our first group of subjects (visuomotor rotation towards the left) for the visual targets respectively located at 45, 135 and 180 degree. Figures (d), (e), (f), (g) and (h) represent our second group of subjects (visuomotor rotation towards the right) for the visual targets respectively located at 0, 45, 90, 135 and 180 degree.

APPENDIX H

EVOLUTION OF THE CURSOR TRAJECTORY

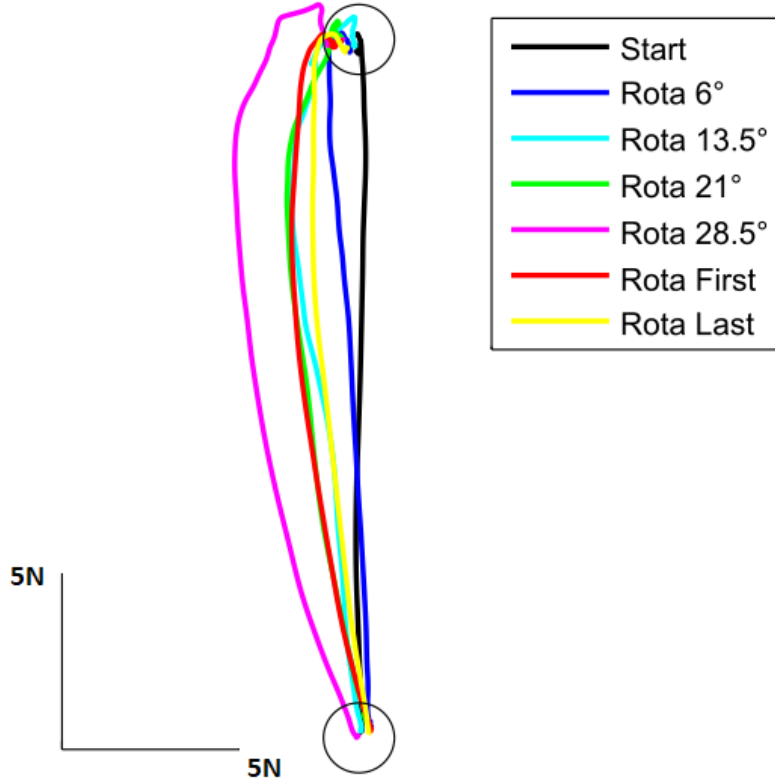


Figure H.1: Cursor trajectory for the upper target at different moments during the experiment, representing different conditions. Black curve is representing the mean trajectory for the 16 trials towards this upper target for our first group of subjects during the first block, without any perturbation. Blue, cyan, green and pink curves are the mean trajectory of the single trial for all the subjects of the first group located at different specific amplitudes of the progressive visuomotor rotation towards the left, respectively 6°, 13.5°, 21° and 28.5°. Red and yellow curves are representing the mean trajectory for the first half and last half of trials towards this upper target for our first group of subjects when the left visuomotor rotation is fixed.

