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Technische Universiteit Delft

Master Thesis

Haptic feedback during training decreases performance in telemanipulation

C.D.J. Stevens

TUDelft

Master Thesis

Haptic feedback during training decreases performance in telemanipulation

by

C.D.J. Stevens

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Preface

I am proud to present this master thesis as the final project for the master track Biomechanical Design as part of the master Mechanical Engineering. After my bachelor's degree in Aerospace Engineering, I was looking for a master's degree combining engineering and the human. I switched to this master, and I could not be happier with the choice.

In this research, I tried to determine if there is a better way to train for teleoperations. An experiment was performed to test the effect of haptic feedback during the training. Prior to this report, I made a literature report, where I surveyed current research into the areas of training and haptic feedback. This report is made up of two parts: a paper, written in IEEE lay-out, and appendices. The paper contains an introduction, the experimental design, and the results and discussion, while the appendices are used to give more detailed information about the entire process.

This master thesis is written under the supervision of Tricia Gibo and David Abbink. I would like to thank them both for sharing their experience, enthusiasm and motivation in this process. Even though there were ups and downs, I will look back at a time were I have learned a lot (both about myself and about the material). Especially in the last few weeks leading up to the moment I finished this report, David Abbink really motivated me to reach for a higher level.

Colleen (C.D.J.) Stevens,
24 April 2018, Delft

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Haptic feedback during training decreases performance in telemanipulation

Catharina D.J. Stevens , Tricia L. Gibo and David A. Abbink

Abstract—Teleoperation allow us to manipulate environments that cannot be manipulated directly by a human operator, like space and deep sea, but they are also used in surgery to scale movements and filter out unwanted movements. Commercial teleoperators often lack haptic feedback to the user. Literature shows that a lack of haptic feedback can reduce fine motor control as a result of missing neuromuscular feedback, and can impair training due to a reduced capability to build accurate internal model of the slave dynamics. Current research often focusses on haptic guidance or training for applications with haptic feedback there has not been found a way to improve training for applications that lack haptic feedback. We hypothesize in this study that simulating haptic feedback during a training phase for execution without haptic feedback, is beneficial in terms of the learning process and the performance. The added haptic feedback in the early stages decreased performance at the end of the training phase and in the generalization phase. Therefore, there is no benefit of adding haptic feedback in the early stage of training when training for a task without haptic feedback.

Index Terms—Teleoperation, haptic feedback, motor skill learning.

1 Introduction

Teleoperation allows us to manipulate environments that cannot be manipulated directly by a human operator, like space, deep sea and nuclear environments. Teleoperation can also be used to scale movements, and is also used in surgery, where unwanted movements of the surgeon can be filtered out and movements can be scaled for more precise movements during surgery.

Since the tool used to manipulate the environment is not directly operated, the natural haptic feedback is lacking in teleoperation. While in theory it is possible to feed back the haptics to the operator, in a lot of commercial applications this is not done because it is too expensive or too complicated. Examples are Underwater Robotic Vehicles (URV), used in the maritime industry and oil and gas industry, and the Da Vinci surgical system etc. [1], [2]

The lack of haptic feedback also impairs the training, and increases training time and performance due to a reduced capability to build an accurate internal model [3]. This paper explores an alternative way of training, using haptic simulators. The hypothesis is that by simulating the natural haptic feedback that will be unavailable later on, users will build up a more accurate internal model, thereby benefiting them when haptic feedback is unavailable.

The underlying mechanism of training is often considered to be the internal model. According to Wolpert et al. (1995) an internal model is "an internal simulation of the dynamic behaviour of the motor system in planning, control, and learning" [8]. This model predicts the movements that need to be made in order to execute a desired movement. When a person is interacting with a system he has never interacted with before, the internal model still needs to be developed - this is called training. In 1995, Wolpert et al (1995) demonstrated the existence of an internal model using a forward model with which they could reproduce the results of human movements [8]. Data from different senses is used to form, and later fine tune, the internal model. Vision, hearing, and feeling are all frequently used sources. However, all these sources contain noise when they get to the brain, complicating a correct sensory estimate of the state. The theory of sensory integration states that the brain combines the information of both sensory streams to reduce the uncertainty of the state [13]. In a system without natural haptic feedback of the dynamics (a teleoperated system), one of the main data sources is missing.

Studies like [5], [7], [21] and [18] find a longer training time and lower performance in subjects training without haptic feedback, compared to training with haptic feedback. This may be caused by the lack of haptic feedback, causing a less accurate estimate of the system state, reducing the capability to build an accurate internal model of the dynamics. On the other hand, the haptic feedback can also cause a different strategy. Due to the presence of the forces exerted by the object on the hand, the biomechanics of the arm and the reflexes may be used to move the mass. This is not possible in the absence of haptic feedback, where subjects have to work with visual feedback alone. Danion et al. (2012) look at the effect of haptic feedback during training, and the effect of the order of the feedback and lack thereof [9]. The task was a reaching task where subjects had to bring an object, connected to the hand through a mass-spring-damper system, to a target. Strom et al. (2006) have performed an experiment with a similar set-up, only subjects trained for a laparoscopic task [7]. Both studies found that haptic feedback in the early stage improves performance in a visual-only environment, compared to training the other way around - vision only first, haptics later. This could indicate a positive effect of haptic feedback, when the task is followed by a task without haptic feedback.

There are multiple types of training. Observation is one of the easiest ways of training. Trainees are showed what they have to do and they try to reproduce the movement. However, this is hardly sufficient for most complex motor skills, and subjects need additional training, perhaps in a simulator. Training on-the-job is still used, but often expensive and dangerous [1].

Almost all other training methods use a simulator to train subjects, before the subjects are brought in the real environment. Often these simulators are not very representative, like the box trainers used for laparoscopic surgery training [5]. Virtual reality simulators show the most potential for training, since the true environment can be approximated best. For motor tasks with haptic feedback, it is known that the training environment should look as much as the real environment as possible, for the best performance [6], [7], [17]. For tasks with haptic feedback, this means that there should be haptic feedback in the training environment as well [3]. By analogy, tasks without haptic feedback should also be trained without haptic feedback. This way of training is however very time consuming, often very expensive and

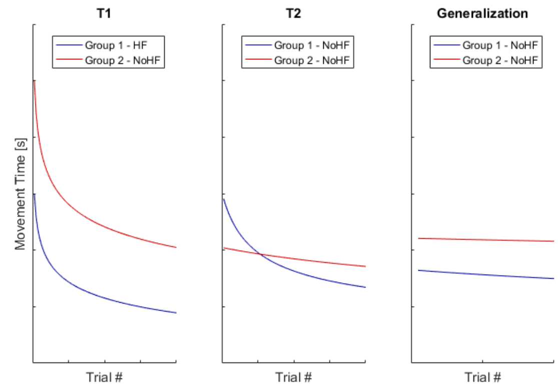


Fig. 1. Visualization of the hypotheses. It is expected that group 1 will have a lower movement time in the last trials of T2. In the first training phase, T1, the group with haptic feedback is expected to have a lower movement time throughout the phase. In T2, the haptic feedback is removed. Therefore it is expected that subjects in group 1 have to adjust, but will end up being faster than group 2 at the end of T2. In the generalization phase, a smoother transfer is expected for the group 1.

does not reach the same level of performance as motor tasks with haptic feedback [9], [17]. Perhaps there is a better way of training for tasks without haptic feedback?

Training in a simulator has a lot of advantages over training on-the-job. It is cheaper and safer to practice the required skills on a simulator instead of on-the-job. An example is URV (Underwater Robotic Vehicle) training. These vehicles are operated from a surface vessel to do inspection and repair of underwater structures for the oil and gas industry. Operators have to perform very complex movements, and this takes a lot of time to learn and to execute [1]. Therefore, training in a simulator is a good alternative for training on the job.

However, an environment can never exactly be simulated. Therefore, in this experiment, a generalization phase is added. In this phase, the dynamics are slightly different from the dynamics used during the training phase. In the 'real world', a person would be training in a simulator and later transfer to the real task - where the dynamics are always a little different. This same principle is included in the experiment design, to see if the learned task also transfers to a slightly different task.

The objective of this study is to see what the effect is of haptic feedback in the early stages of training, for a task without haptic feedback.

It is hypothesized that adding haptic feedback in the early stage of training will results in a better movement time at the end of the training. Since a simulation is always different from the system that is being simulated, a generalization phase is added with different dynamics. It is hypothesized that the haptic feedback will also result in a smoother transfer to a task with slightly different dynamics. In the first stage of training the haptic feedback will improve the performance with respect to the control group without haptic feedback. When the haptic feedback is removed in the second stage of training, it is expected that it will take a few trials to adjust to the new conditions, but that the learning curve will continue and the performance will be better than that of the control group. Furthermore, it is expected that both groups have a different approach on how to move the mass (strategy). The hypotheses are summarized below, and visualized in figure 1. The experimental protocol is elaborated on in section 2.

- It is beneficial to add haptic feedback in the first stages of training, when training for a task without haptic feedback. Subjects will improve performance (movement time) when compared to subjects training without haptic feedback.
- In the first stage of training, the group training with haptic feedback will have a lower movement time than the group training without haptic feedback.
- In the second stage of training, the haptic feedback is removed for group 1. It is expected that it will take a few trials to adjust to the new condition, but that the learning curve will continue and the performance will be better than that of the control group.
- Both groups will improve in the generalization phase, but group 1 will improve more and have a lower movement time.
- There will be a difference in the way both groups move the mass. Subjects from group 1 will let the hand move away from the object, while subjects from group 2 will keep the mass close to the hand.

2 Methods and Materials

2.1 Subjects

Twenty subjects (18 female, 2 male) participated in the experiment (age 20 to 29 years). They were randomly assigned to one of two groups, Group 1 and Group 2. The groups are further explained in section 2.3. The Delft University of Technology Human Research Ethics Committee approved the experiment. All subjects signed an informed consent form before starting the experiment.

2.2 Apparatus

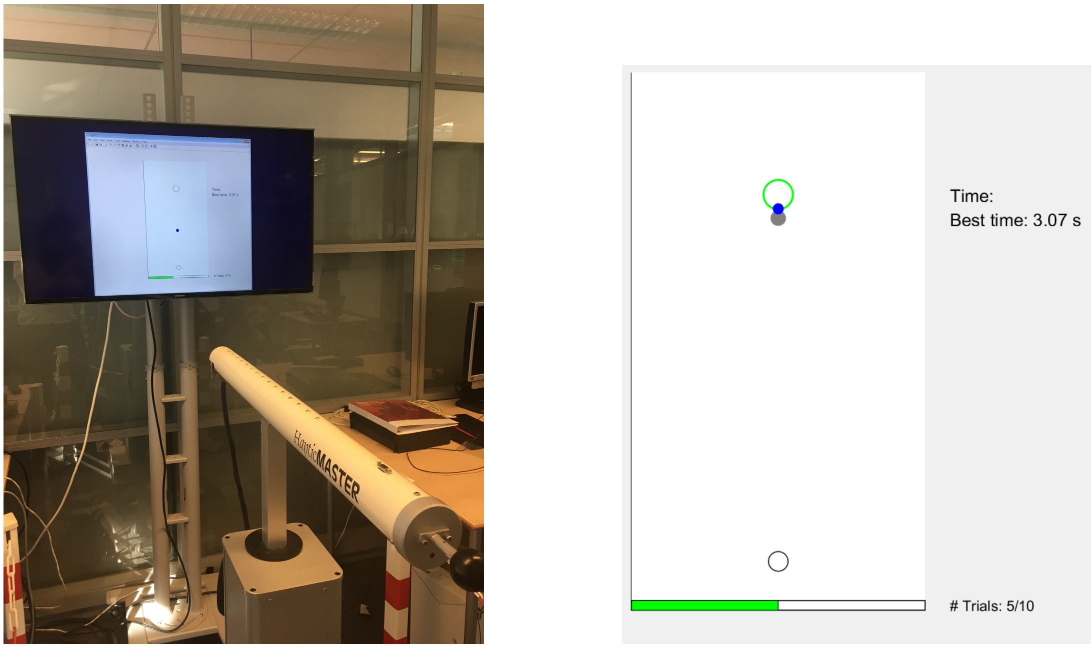
For the experiment, the "HapticMaster" was used. This device contains sensors and actuators to measure force and position of the operator, and to and to render simulated dynamics of a virtual system controlled by the handle. The device runs on a PC with VxWorks realtime operating system, with an update rate of 2500 HZ [14]. The positions and forces are calculated real-time by a processor, the real-time Bachmann GmbH. This processor calculates the forces and positions through a virtual model of the dynamics made in Simulink. The movement of the HapticMaster was restricted a one-dimensional movement (in the x-direction).

2.3 Experimental Task and Protocol

Subjects were asked to move a virtual mass, connected to the hand (the HapticMaster) through a mass-spring-damper system, from the start to a target. The positions of the hand and the mass, as well as the start and target were shown on a monitor in front of them. Figure 2b gives an overview of the start, target and the visualization of the hand and object's position.

Before the start of the experiment, subjects had a familiarization phase of ten trials. In these ten trials, there was no virtual object attached to the hand.

The experiment is divided in four phases: the familiarization phase, two training phases and a generalization phase. Group 1 trained the first 80 trials with force feedback of the natural dynamics, while group 2 trained the first 80 trials without haptic feedback. In the second training phase and the transfer phase, both groups trained without haptic feedback. An overview of the experimental design can be found in figure 3. In the last phase, the transfer of generalization phase, the dynamics of the mass-spring-damper system were slightly changed. This is done to test if the motor skill learned in the training phases, can be applied to similar tasks. During training, the mass and stiffness were 3 kg and 120 N/m. In the generalization phase this was changed to 6 kg and 60 N/m, respectively. The damping was always 1 n/m/s. The experiment was designed to be similar to the experiments by Danion et al. (2012) and Dingwel et al. (2002) [9], [15].



(a) Overview of the screen and the Haptic-Master

(b) Visualization to the participant

Fig. 2. Experimental set-up. Figure 2a shows the set-up of the screen with the HapticMaster. In the right lower corner, the black knob can be seen that the subjects use to move the HapticMaster. Figure 2b shows the screen in more detail. The green circle is the target, the black circle at the bottom is the start. The position of the master (hand on the knob) and the slave (virtual object) are represented by the grey and blue circle, respectively.

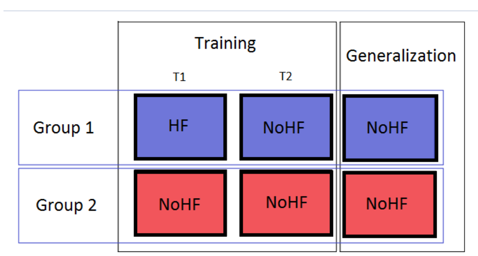


Fig. 3. Experimental design. Each group consist of 10 subjects.

To start the experiment, the subjects had to bring the hand in the start position for 300 ms. When they did this, the target appeared and the trial started. They were instructed to bring the object to the target as fast as possible. The distance between the start and the target corresponded to a movement of the hand of 15 cm. Once the object had reached the target and stayed there for 150 ms with the speed of the object below 2 cm/s, the trial was ended and the target disappeared. Also, the virtual mass, attached to the hand, was disconnected. The subjects could then, at their own pace, move the hand back to the target to start another trial.

After every trial, the movement time of the last trial was shown. Also, the best overall movement time was shown. Movement time was defined as the time between the point where the target appeared and the target disappeared.

2.4 Data Analysis

The time ($t[s]$), forces applied by the hand (F_h[N]) , the position (x_h[m]) and velocity(v_h[m/s]) of the knob, calculated position (x_o[m]) and velocity (v_o[m/s]) of the object and forces applied by the object [F_o[N]] on the hand are sampled at a rate of 1000 Hz.

Before starting the data analysis, the data is smoothed using a fifth order Butterworth filter with a cut-off frequency of 10 Hz [16].

A second order polynomial curve, $p(x) = p_1x^2 + p_2x + p_3$, was fitted through the averaged movement times.

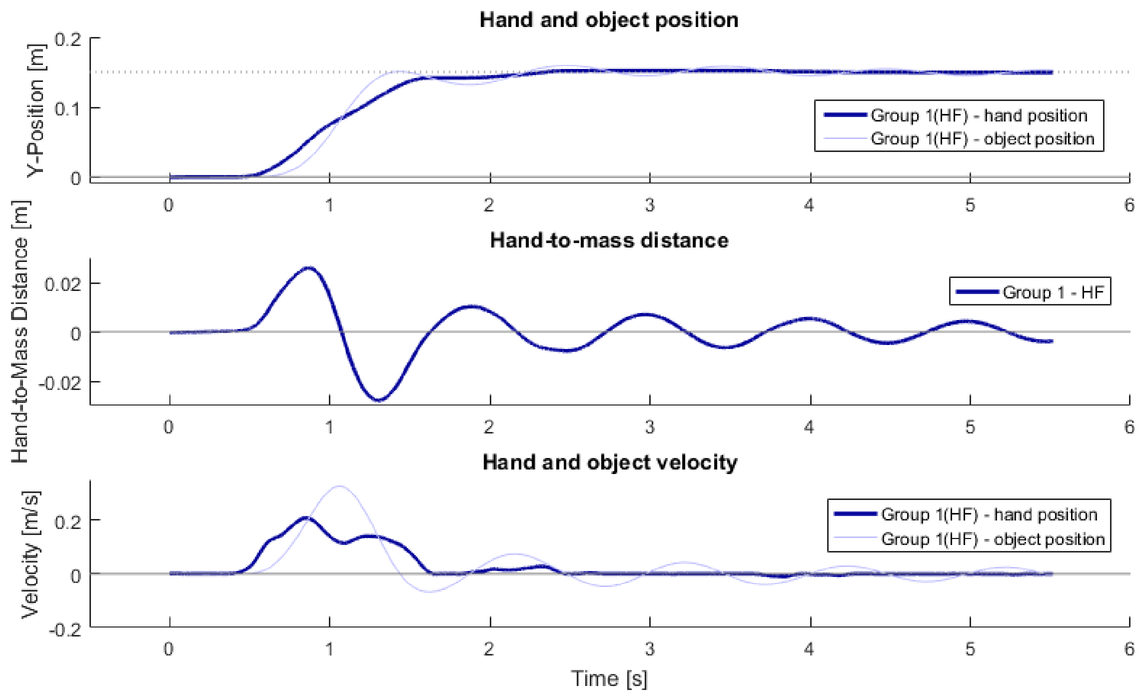


Fig. 4. Example of a representative trial. The hand and object position are shown, as well as the hand-to-mass distance and the hand and object velocity. This data is taken from subject 19(group 1), trial # 8 (T1). This means that this is a trial where the subject has haptic feedback available.

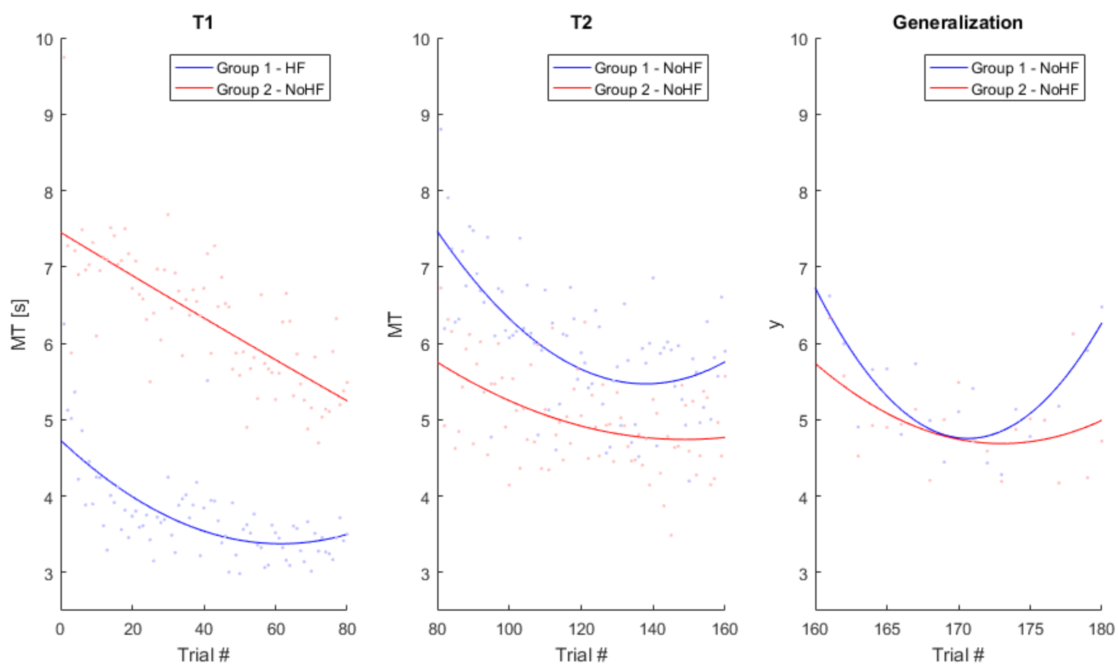


Fig. 5. Averaged movement times for the two training phases and the generalization phase. Movement times are averaged per five trials, for all 10 subjects per group. A polynomial curve is fitted through the results.

To test the data listed below, a Mann-Whitney U-test was used for a significance level of $\alpha = 0.05$.

The metrics tested are the following:

- Movement Time t_m): the time between the

start and end of a trial
- y-distance between hand and object, $\Delta y = x_h - x_o$
- hand velocity v_h
- reach time t_r: the time needed to reach 90 % of the target distance.
- damp time $t_d : t_m - t_r$

3 Results

Figure 2.3 shows an example trial. The hand and objects position (x_h and x_o) are shown, as well as the hand-to-mass distance (Δy) and the hand and object velocity (v_h and v_o).

3.1 Movement time analysis

To test the hypothesis about the performance at the end of T2, the movement times are compared. The movement times are shown in figure 5. The movement times are averaged over all 10 subjects and grouped per 5 trials. For the last 10 trials of T2, group 2 has a lower movement time than group 1 ($p < 0.01$), which can be seen in figure 5.

In the first stage of the training, group 1 has a lower movement time than group 2 for all 80 trials ($p < 0.01$). Both groups improve their movement time during this part of training: Group 1 from 4.7310 s (first 10 trials) to 3.4017 s (last 10 trials)($p < 0.01$), and group 2 from 7.1895 s to 5.4069 s ($p < 0.01$).

After 80 trials, the haptic feedback of group 1 is removed. This causes the movement times to rise 210 % to 7.1685 s($p < 0.01$). After 160 trials, there is a significant difference in movement times between group 1 (MT = 5.6706 s) and group 2 (MT = 4.8136 s), $p < 0.01$. Both groups improve their movement time during this part of training: Group 1 from 7.1685 s (first 10 trials) to 5.6706 s (last 10 trials), $p = 0.0318$, and group 2 from 5.5732 s to 4.8136 s ($p < 0.01$).

The transfer from the training to the generalization phase is smooth for group 1 (there is no significant difference in movement times, δ MT = 0.0970 s, $p = 0.169$). This is different for group 2: the movement times is increased by 110%, from 4.8136 s to 5.2495 s ($p = 0.007$).

In the generalization phase, group 2 keeps improving in the generalization phase ($\delta MT = 0.4007s, p = 0.0102$, indicating that they are still learning. Group 1 has no significant difference between the first and last five trials of the generalization phase($\delta MT = 0.0320s, p = 0.8887$).

Both groups experience a learning curve in each phase (HF T1 $p < 0.01$, HF T2 $p = 0.0318$, NoHF T1 $p < 0.01$, NoHF T2 $p < 0.01$, NoHF transfer$p = 0.0102$) except for group 1 in the generalization phase ($p = 0.8887$).

3.2 Hand velocity and distance

To see if there is a difference in the way subjects move the mass, the hand-to-mass distance is calculated (Δy) , as well as the hand velocity. Figure 6 shows the median hand velocity and the median hand-to-object distance.

The upper plots show the hand-to-object distance. There is a significant difference between group 1 and group 2 at the start and end of T1 ($p < 0.001$) and the start of T2 ($p < 0.001$), but at the end T2 there is no significant difference ($p = 0.34$). Also in the generalization phase, there is no significant difference between both groups ($p = 0.29$).

The lower plots show the median hand velocity. In T1, group 1 has a higher velocity than the group 2 ($p < 0.001$). In T2 however, the velocity of group 2 is higher at the start ($p < 0.001$) and at the end ($p < 0.001$). In the generalization phase this difference continues ($p = 0.009$).

3.3 Strategy / reaching and damping phase

Figure 7 shows the movement times, divided into a reaching phase and a damping phase. How these are calculated is explained in section 2.4. There is no difference between groups 1 and 2 in the generalization phase for both damping and reaching phase ($p = 0.06andp = 0.11$, respectively). At the end of T2, there is no difference between the two groups in the damping phase ($p = 0.06$) while there is a difference in the reaching phase ($p = 0.007$).

4 Discussion

In the first part of the training, there was a clear difference between the two groups. As previous research already showed, the group training with haptic feedback had a better performance (lower movement time) than the group training without haptic feedback[[3], [15]].

It was expected that group 2 would continue their learning curve, until they reach a plateau. This plateau is reached after approximately 120 trials, as can be seen in figure 5. For the group 1, it was expected that they would have to adjust to the new situation, when the force feedback was removed. This is indeed what happened, but after this the results are different from what was expected. It was expected that the group 1 would adjust quickly to

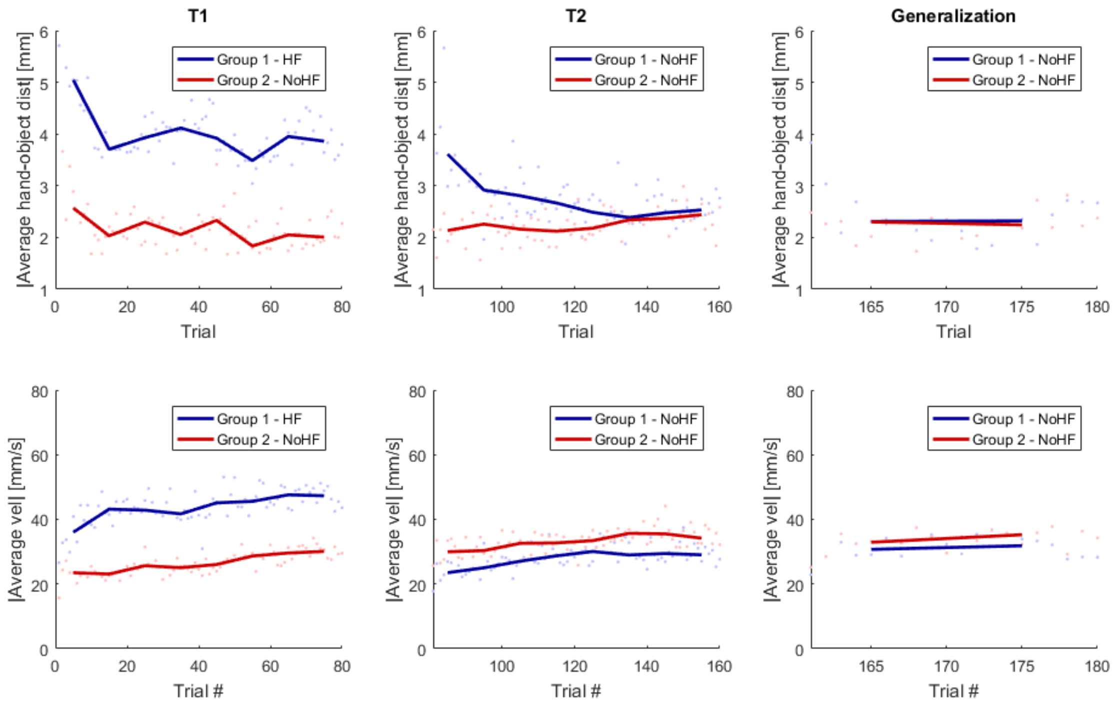


Fig. 6. Median hand-to-object distance (upper plots) and the median hand velocity (lower plots) are plotted for both training phases and the generalization phase.

the new situation and, because of the additional information in the first part of training, would have a better internal model, and therefor perform better that group 2. This is however not what happened, as group 1 had a higher movement time at the end of T2.

The transfer to a system with different dynamics (in the generalization phase) was however smoother for group 1 than the transition for group 2. Group 1 did not improve performance during the trials in the generalization phase, while group 2 had a less smooth transfer, but they did improve their movement time and, at the end of the generalization phase, did have a better movement time than group 1.

Figure 7 again shows the movement times for all subjects per group, only the movement is now divided in a damping and a reaching phase. The movement is divided in these two phases, mimicking a step response. The first phase, the reaching phase, is where the subjects make a fast hand movement to get close to the target. Once the object is withing 90 % of the target distance, the reaching phase starts. In this pahse the subjects will start to damp out the oscillations to get the object in the target, with the right velocity. Figure 2.3 (upper plot) shows the hand and object movement of one trial. There, the different phases can clearly be distinguished.

Figure 6 shows the average hand-to-object distance (Δy) and the hand and object velocity ($v_h and v_o$). As discussed in section 3, there is a significant difference in Δy between group 1 and group 2. This means, that the groups have a different approach in the way they move the hand and the object. Group 1 has a higher Δy in T1, meaning they let the hand and object move further apart than group 2. In T2, the Δy from group 1 decreases, and approaches the Δy of group 2. In the last 30 trials, there is no difference between the two groups for this metric.

Figure 7 (upper left) shows that group 1 has a lower reaching time in the first part of training. This is caused by the feedback they receive. Since they have haptic feedback available, their reflexes are used to damp out the oscillations, and therefore, their overall movement time is shorter. Group 2 has a higher movement time in the reaching phase. They move slower to cause smaller accelerations, which causes less oscillations for the objects attached to the hand. This way, they can reach almost the same damping time as group 1, using visual feedback only (figure 7, lower left). Note that, even though they have to damp out smaller oscillations, they still have a higher movement time spent in the damping phase. This is, because these subjects cannot use their reflexes to damp out the oscillations: they only have visual feedback available.

With the transfer to the second training phase, a few things change. In this phase (T2, middle figures), group 2 will keep on perfecting the movement. They have already found a strategy that worked in the first part of the training, and can keep on improving. Their learning curves will continue to improve until the plateau is reached. Group 1 however, needs to adjust to the new conditions. The haptic feedback is removed, so they cannot use their reflexes to damp out the oscillations of the virtual object. This can be seen in the damping phase: subjects from group 1 need more than twice as much time as the subject from group 2 in the first trials of T2.

In the generalization phase, there is no difference in movement times between the groups, both for the reaching and damping time.

Perhaps it helps to have group 1 train a little longer in the conditions of T2 (without haptic feedback). They may just need a little more time to reach the same level as group 2. When looking at the learning curve, it can be seen that group 1 reaches a plateau around 125 trials. Therefore, it is very unlikely that more training will improve their performance.

But why is it that group 1 performs not as good as group 2, even though they have the haptic feedback to help build the internal model in T1? What was expected, was that group 1 would learn, with the use of the haptic feedback, an internal model with the best way to damp out the oscillations in T1. In the first trials of T2, they would have to adjust to the new conditions and would have a higher movement time than the group 2, but once they would adjust to the new conditions, their movement time would improve. Perhaps they had to adjust their reaching movements a little : maybe they start out faster than group 2 at the start of T2, but they will slow their movement down a little. At the end of T2 though, a faster total movement time is expected.

What can be seen though, is that group 1 indeed starts of with a higher reaching time. They do not improve the time spent in the reaching phase though, and end up having a higher reaching time. The same effect can be seen in the damping phase. It can be seen that, compared to the reaching phase, group 1 shows a significant learning curve in the damping phase. The time spend in the damping phase is still higher than that of group 2 at the end of T2.

This can mean that the subjects in group 1 do not learn how to correct the damping in the first stage of training. Since they can use their reflexes to damp out the oscillations, there is no reason to learn how to do this. In the mean time, group 2, without haptic feedback, has more time to learn a correct strategy and can use T2 to perfect their movements.

But how is it possible that Strom et al. (2006) and Danion et al. (2012) both find a positive effect of haptic feedback early in the training? This can be explained by the experimental design. Both experiments have two groups with two training stages. The difference between the two groups is the order of training: one group trains first with haptic feedback, later without (only visual feedback) while the other group trains the other way around. At the end of each training phase, their performance is evaluated. This means, that when the two groups are compared in the same condition (e.g. vision only), one group has had one training session (vision only), but the other group has had two training sessions (haptics-vision, vision only). This is visualized in figure 8a. When the results of the HV task (blue) are compared, group 1 has had 1 training session, while group 2 has had 2 training sessions.

When looking at the results shown in figure 8b, is that the HF-V group performs better in the V condition (red) than the V-HF group. In a previous literature study, it was theorized that this is because there is an advantage of having haptic feedback in the early stage. Another reason for the difference between the groups may simply be because they have trained for twice as long. However, when you look at the HV condition (blue), this results cannot be found. Look at the HV condition (blue): There is no difference in movement times between the groups, even though the V-HF group trained twice as long. This was interpreted as there being a benefit of haptic feedback in the early stage of training. It can however be also interpreted the other way around: perhaps there is no effect/a very small effect of first training with visuals only, when you are training for a task with haptic feedback.

This experiment consists of three phases: two training phase and a generalization phase. This was done to mimic a 'regular' training process: users are

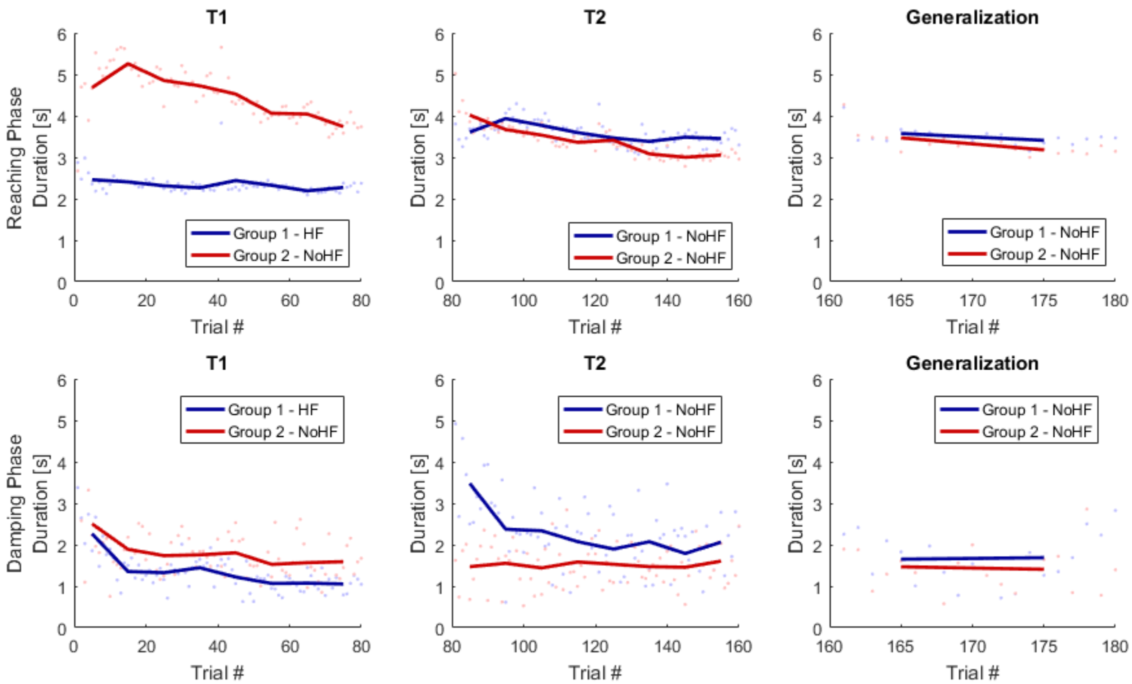
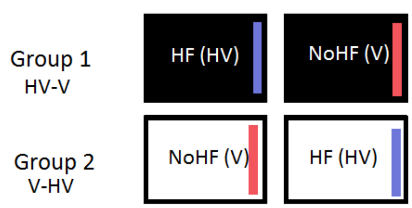
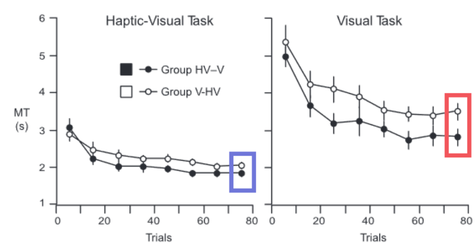


Fig. 7. Movement times divided in the reaching and the damping phase



(a) Experimental set-up of the experiment by Danion et al. (2012) [9]



(b) Results of the experiment by Danion et al. (2012) [9]

Fig. 8. The set-up and results of the experiment by Danion et al. (2012) are shown. In the results, two similar conditions are compared (HV-task or V-task), respectively blue and red.

often training in a simulator or a virtual environment, and after that, they have to perform in the real environment. This real environment is never exactly the same as the training environment. To mimics this in the experiment, the dynamics were different in the training phases and the generalization phase. While the differences between the two groups were quite big during training, in the generalization phase these differences disappeared. At the end of the 20 generalization trials, group 2 even had a slightly lower movement time, while it was hypothesized that group 1 would have a better performance (i.e. lower movement time).

This means, that even though it may be possible to have subjects train with haptic feedback, it is still better to have them train without haptic feedback. There is no benefit of the additional information in the first stage of training.

5 Conclusions

A between-subjects haptic telemanipulation experiment was performed to show the effect of natural haptic feedback during the first stage of training for a task without the natural haptic feedback. Subjects were divided into two groups, and asked to repeatedly execute a reaching task. This was done using a master-slave system, where the master and virtual slave are connected through a virtual mass-spring-damper system. For the experimental conditions studied, the following conclusions are drawn:

- **There is no benefit in adding haptic feedback during the first stages of training, when training for a task without haptic feedback. Adding haptic feedback in the early stage of training results in a higher movement time at the end of training, compared to training without haptic feedback.**
- In the first stage of training, the group with haptic feedback has a shorter movement time.
- In the second part of the training, the haptic feedback is removed. There is no smooth transfer for group 1 - there is an increase in movement time of 210 %. Both groups show a significant learning curve from the beginning to the end of this phase, but at the end of the training the movement times from group 1 are significantly lower than the group 1.
- In the generalization phase, there is no learning curve for group 1, while group 2 keeps improving and ends with a better movement time than group 1.

Acknowledgments

I would like to thank my supervisors for sharing their knowledge about the subject, and their enthusiasm and motivation. I learned a lot from the conversations and meetings with them during this project.

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A

Experimental setup

In this appendix, the experimental set-up will be explained a little more. The experimental protocol is explained before, in the 'Methods' section.

A.1. Experimental set-up

In this experiment, a teleoperator is used. A teleoperator consists of a master and a slave. The master is the interface where the human (the operator) is operating, while the slave is the part operating in the (remote or virtual) environment[2]. They are connected through a controller.

In this experiment, the Haptic Master by Moog is used. The slave is a virtual mass-spring damper system. An overview of the set-up is shown in figure A.1.

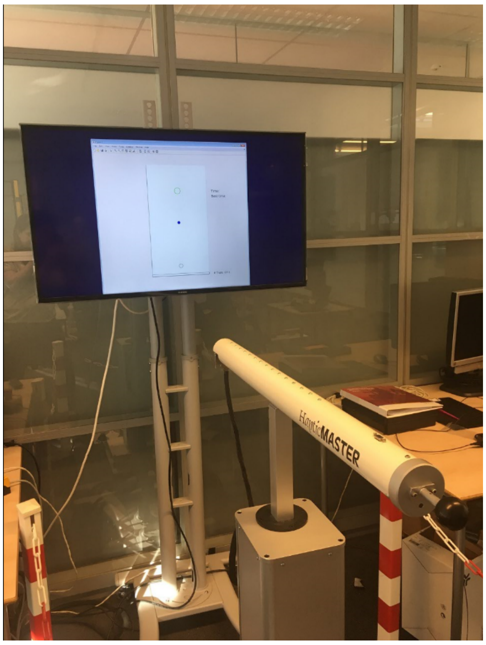

Figure A.1: The master (HapticMaster by MOOG) and the slave (virtual environment, shown on the monitor).

Haptic Master

The HapticMaster is a 3 DoF-device, equipped with a standard end-effector. The HapticMaster is an admittance controlled device, which means the displacement of the device is calculated by the amount of force applied to the device. The device runs on a PC with VxWorks realtime operating system, with an update rate of 2500 HZ [3].

Table A.1: Overview of the positions and sizes of the objects used in the visualization (see figure XX)

Diameter	Value
Start (diameter)	14 [mm]
Target (diameter)	20 [mm]
Hand position	10 [mm]
Virtual mass	7 [mm]

Virtual Slave

The slave used in the system is a virtual mass-spring-damper system, depicted on a monitor. This is described in more detail in section A.2.

Bachman and Computer

The Haptic Master runs through real-time processors, the Bachman GmbH. This ensures that the system can be controlled through a Simulink environment. The design of this system will be described in appendix D.

A.2. Feedback Types

Visual Feedback

The movement of the mass and the object were shown on a screen in front of the subjects, as well as the target and the start of the reaching task. See figure A.1 for an overview. Next to these visuals, on the right side of the screen the movement time was shown after completion of each trial. Furthermore, the best time of all trials was shown below. Figure A.2 shows the screen in more detail. The sizes of the objects shown on the screen are detailed in table C.2.

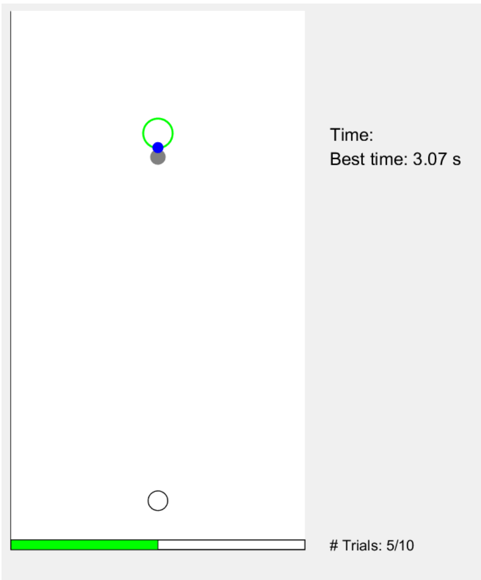

Figure A.2: Details of the visualization for the user. The green circle at the top is the target, the black circle at the bottom is the start. The grey and blue dots are the hand and the object, respectively.

Haptic Feedback

Next to the visual feedback that all subjects receive, one of the two experimental conditions also has haptic feedback during one of the training phases. This is haptic feedback of the natural dynamics of the system. The model and equations of motion used to simulate this, are discussed in section **??**.

B

Pilot Experiment

Before the experiment is conducted, a pilot experiment is done to see if changes need to be made before testing multiple subjects.

B.1. Experimental Protocol

Two subjects were asked to perform the pilot experiment, one for each experimental group. Both subjects trained in two phases, both of 80 trials. The task is described in the methods and materials section (chapter 1) . After this, they were asked to perform the same task (10 trials) only the dynamics were adjusted slightly. Group 1, the HF group, trained with haptic feedback the first training session. After these first 80 trials, the haptic feedback was removed. Group 2, the NoHF group, trained both sessions without haptic feedback. In the generalization phase, there was no haptic feedback available as well. See figure B.1 for a schematic of the two groups.

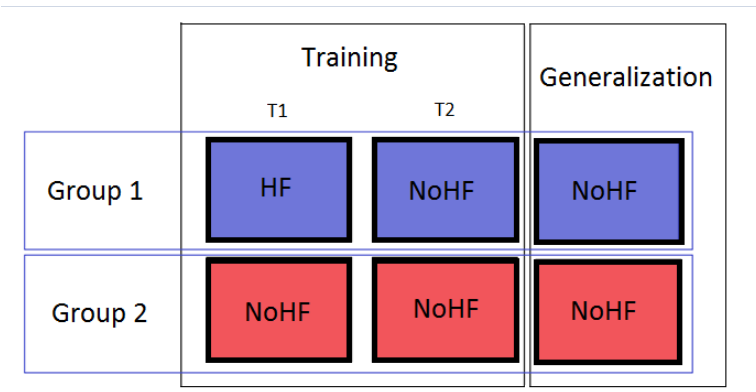

Figure B.1: Schematic of the two experimental groups.

B.2. Pilot Results

Figure B.2 shows the results for one trial. Both groups are shown in the same figure. These trials are taken from the first training phase, where subject 1 (from group 1) has haptic feedback available and subject 2 (from group 2) does not. What can be seen, is that subject 1 reaches the target faster than subject 2. At the start of the trials, their acceleration is higher, causing the object to move further from the hand - they can do this, since they have the haptic feedback available to help damp out the oscillations this is causing.

Figure B.3 shows the pilot results. The individual movement times are plotted, as well as a second order polynomial fit through the data points. As described in the introduction, subject 1 is faster in the first stage of the training. Since they have haptic feedback available, this was expected. In the second

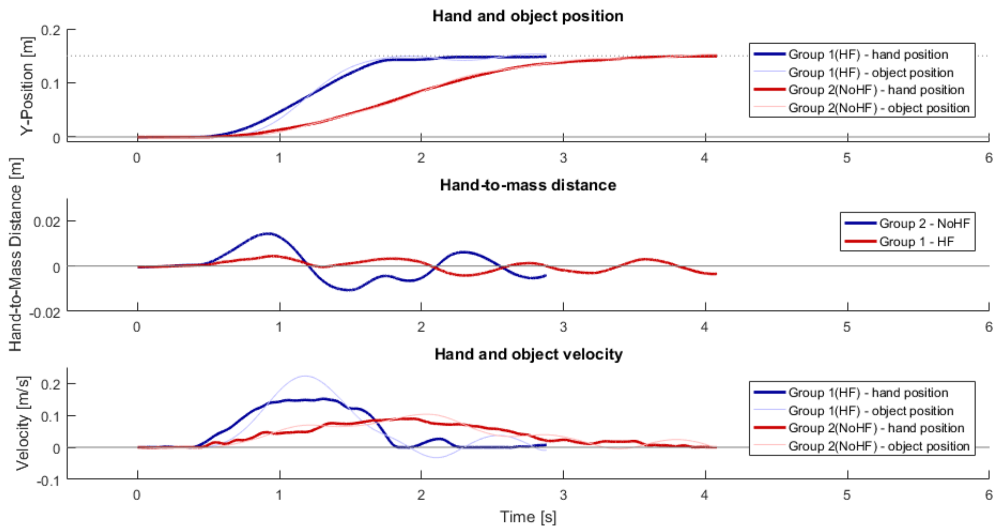

Figure B.2: Raw data of the hand and object position, velocity and hand-to-mass distance for one trial.

stage, this subject has an increase in movement time of 260 %. However, they quickly improve and end up with a significantly lower movement time in the last 10 trials of T2 than subject 2 ($p < 0.01$). Also in the generalization phase, subject 1 has a significantly better movement time than subject 2($p < 0.01$).

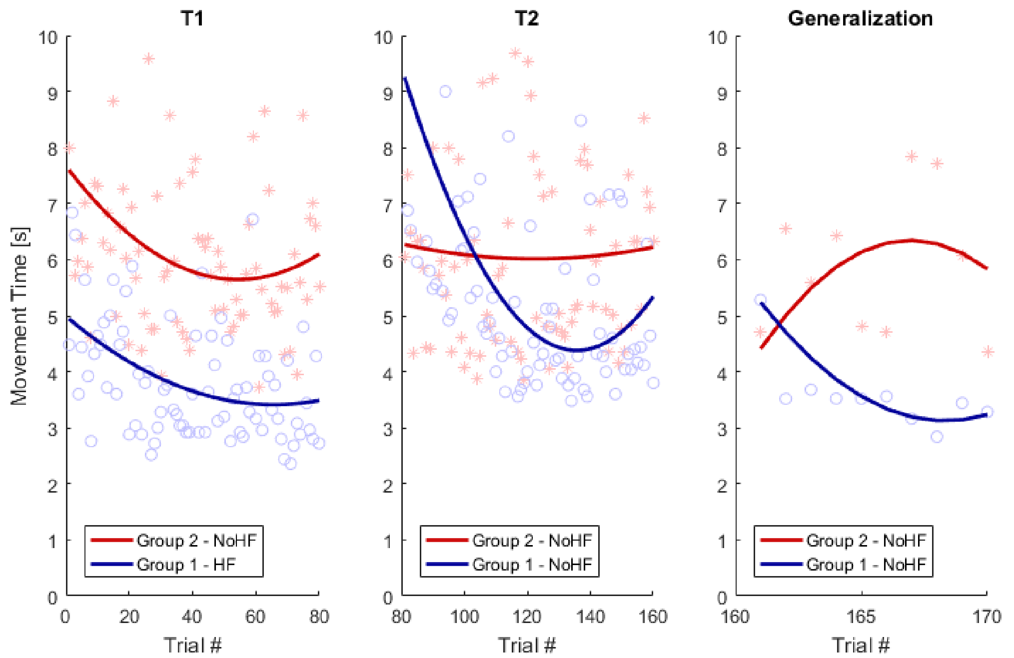

Figure B.3: Pilot results for movement time. Haptic feedback (blue) vs. no haptic feedback (red).

B.3. Conclusion and Discussion Pilot

The expectations that were described in the introduction (chapter 1) seem to correspond to the pilot results. In T1, the subject that has haptic feedback has a lower movement time throughout all 80 trials. This was expected from previous literature [4–6].

In the second stage, the haptic feedback was removed. It was expected that group 1 needed to adjust, but would end with a better movement time that the group that only trained without haptic feedback. See figure 2 for a visualization of the expectations (chapter 1). When looking at figure B.3, it can clearly be seen that this is happening. At the end of T2, group 1 has a significantly better movement time than subject 2. In the generalization phase, it can be seen that subject 1 continues to learn. Group 2 however, has a higher standard deviation in movement times. There is however a small statistical difference ($p = 0.045$), probably because of the small amount of trials. Therefore, the amount of trials in the generalization phase will be doubled.

Alterations for the final experiment

There were a few adjustments needed before the final experiment could start. Firstly, subjects indicated that the task was becoming repetitive and 'boring' after so many trials. Therefore, in the final experiment, a 'competitive' aspect was added [8]. Additional to the movement time of the last trial, their total best time was added so that they would feel the need to keep improving themselves. Furthermore, there was no familiarization phase. In the final experiment this will be added, to get the subjects familiar with the movement that they need to make, the location of the start and the target and the task.

- The number of trials in the third phase (generalization) is changed from 10 to 20.
- 10 practice trials are added before the start of the training. In these 10 trials, the object is not attached to the hand. This way, the subject can get a better understanding of the distance tot he target, the size of the target etc.
- The best movement time will be displayed on the side to stimulate subjects to keep improving their movement time.

C
Results

In this appendix, the experimental results are shown in a bit more detail. Individual plots are shown, as well as additional metrics.

C.1. Movement Time

Figures C.1 and C.2 show all movement times two subjects, one of each group. Table C.1 shows the results for the statistical test of the movement times. In every test, group 1 and group 2 are compared. For each phase, the first 10 and the last 10 trials are tested.

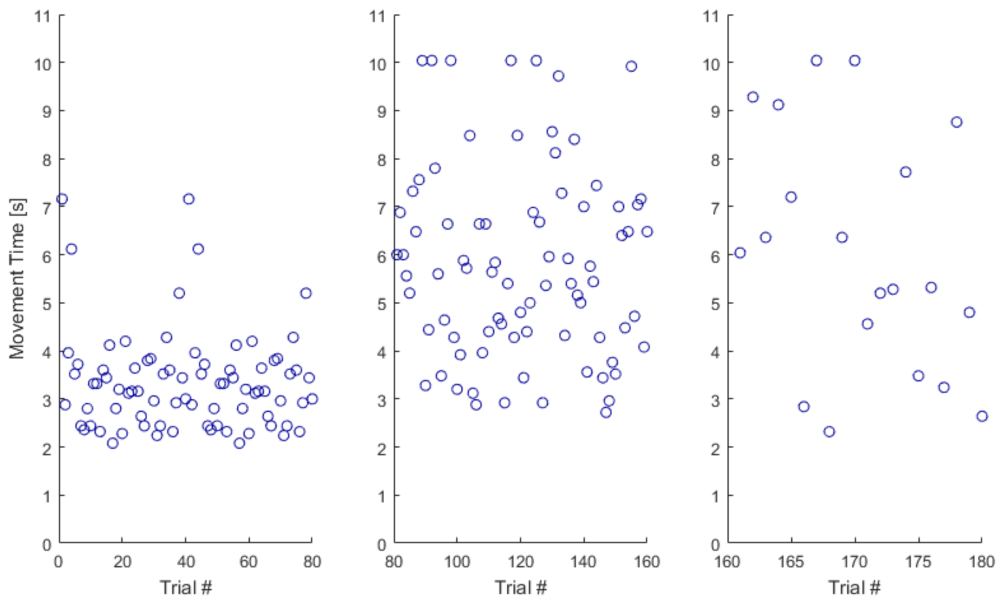

Figure C.1: Raw data of the hand and object position, velocity and hand-to-mass distance for one trial. These are the movement times of subject 1, group 1.

C.2. Position and Velocity

Figure C.3 shows the data from 2 individuals, one from each experimental group. The same format is used as the pilot results, as can be seen in section B.2. The hand and object position can be seen, from one subject in group 1 and one subject in group 2.

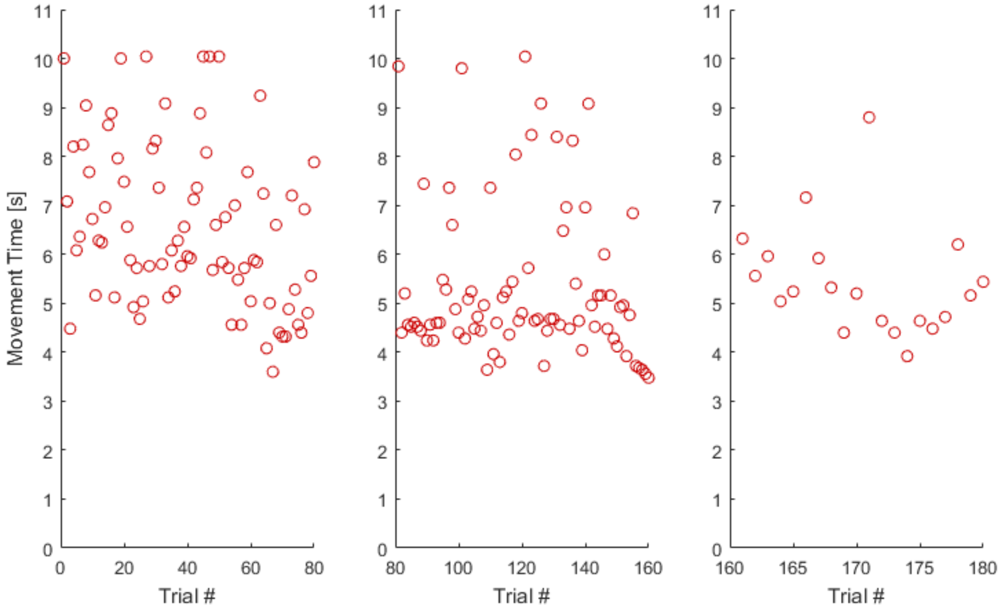

Figure C.2: Raw data of the hand and object position, velocity and hand-to-mass distance for one trial. These are the movement times of subject 2, group 2.

Table C.1: Results of the statistical tests for the movement times between group 1 and 2.

Test	First 10 trials	Last 10 trials
T1	$p < 0.001$	$p < 0.001$
T2	$p < 0.001$	$p < 0.001$
Generalization	$p = 0.2034$	$p = 0.0069$

C.3. Reaching and Damping phase

Figures C.5 and C.7 show the reaching phase and damping phase for two subjects, one for both group, including one standard deviation. Table C.3 shows the results for the statistical tests, comparing group 1 and 2 in different phases of the experiment.

C.4. Learning Curve and Plateau

Both groups show a significant learning curve in all 3 phases. Movement times decreased significantly from the first 10 trials to the last 10 trials (see p-values overview in table C.4). Both groups reach a plateau between 120 and 130 trials. There is no statistical difference between trials 120 to 130 and 170 to 180 for group 1 ($p = 0.3431$), while for group 2 there is no statistical difference between trials 100 to 110 and 170 to 180 ($p = 0.2208$). There is a significant difference per group at the start and end of each phase (group 1, T1 $p < 0.01$, group 1, T2 $p = 0.0318$, group 2, T1 $p < 0.01$, group 2, T2 $p < 0.01$, Group 2, generalization $p = 0.0102$) except for group 1 in the transfer phase ($p = 0.8887$).

C.5. Statistical Tests

To test the data, t-test can be used since a between-subjects experiment is used with two independent groups. A t-test can only be used when a few criteria could be fulfilled [9]. The first criterion is the criteria of normality: data has to be normally distributed. To test this, the Shapiro-Wilk test of normality is used. All metrics as listed in section 2.4 are tested for normality. All of the tests rejected the null-hypothesis, meaning that none of the data sets fulfills the normality criterion.

Therefore, a non-parametric variant of the t-test could be used, the Mann-Whitney U-test [9]. To

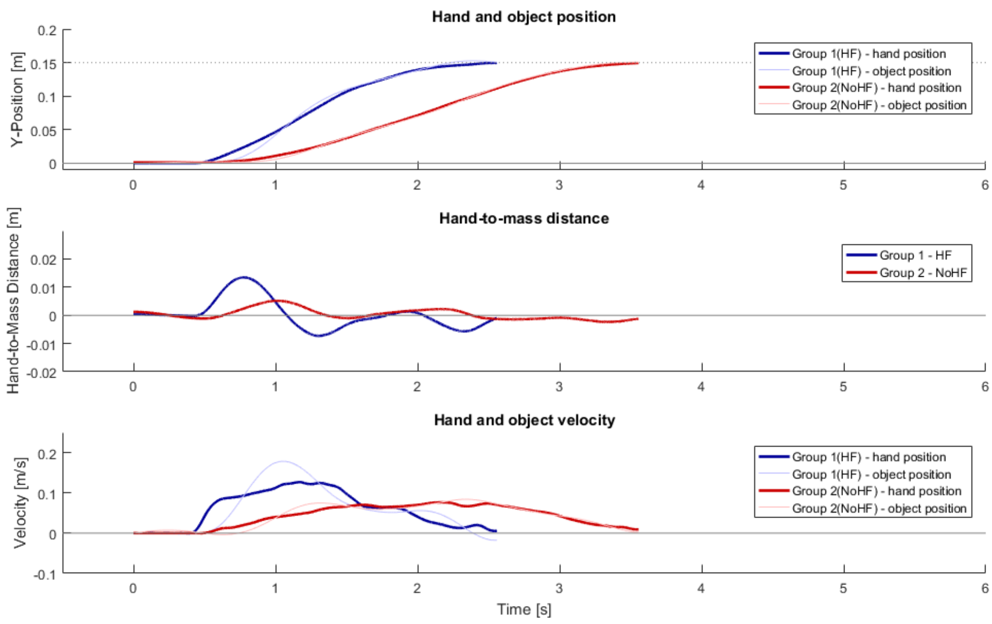

Figure C.3: Example of a representative trial. The hand and object position are shown, as well as the hand-to-mass distance and the hand and object velocity. This data is taken from subject 19(group 1), trial # 20 (T1) and subject 20 (group 2), trials 20.

Table C.2: Results of the statistical tests for Δy and v_h.

Test	First 10 trials	Last 10 trials
T1 (Δy)	$p < 0.001$	$p < 0.001$
T2 (Δy)	$p < 0.001$	$p = 0.3363$
Generalization (Δy)	$p = 0.1448$	$p = 0.2931$
T1 (v_h)	$p < 0.001$	$p < 0.001$
T2 (v_h)	$p < 0.001$	$p < 0.001$
Generalization (v_h)	$p = 0.1962$	$p = 0.0089$

use this test, the data needs to fulfill four criteria:

1. The data should be measured on a continuous scale
2. There should be two independent groups
3. There should be independence of observations
4. The two distributions should be the same shape

All the tested metrics fulfill these conditions.

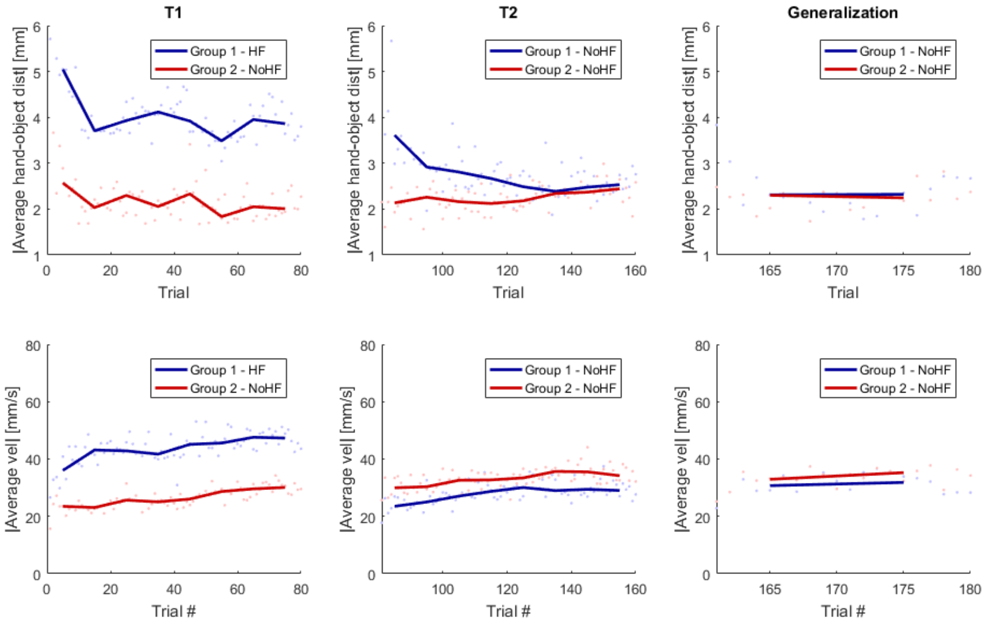

Figure C.4: Median hand-to-object distance (upper plots) and the median hand velocity (lower plots) are plotted for both training phases and the generalization phase.

Table C.3: Results of the statistical tests for the reach and damping time between group 1 and 2. The total results are shown in figure

Test	**First 10 trials**	**Last 10 trials**
T1 (reach)	$p < 0.001$	$p < 0.001$
T2 (reach)	$p = 0.0052$	$p = 0.0071$
Generalization (reach)	$p = 0.6969$	$p = 0.1090$
T1 (damp)	$p = 0.8288$	$p = 0.1006$
T2 (damp)	$p < 0.001$	$p = 0.0578$
Generalization (damp)	$p = 0.5836$	$p = 0.0627$

Table C.4: Learning curve

Phase	**HF**	**NoHF**
T1	$H = 1, p < 0.01$	$H = 1, p < 0.01$
T2	$H = 1, p = 0.0318$	$H = 1, p < 0.01$
Transfer	$H = 0$	$H = 1, p = 0.01$

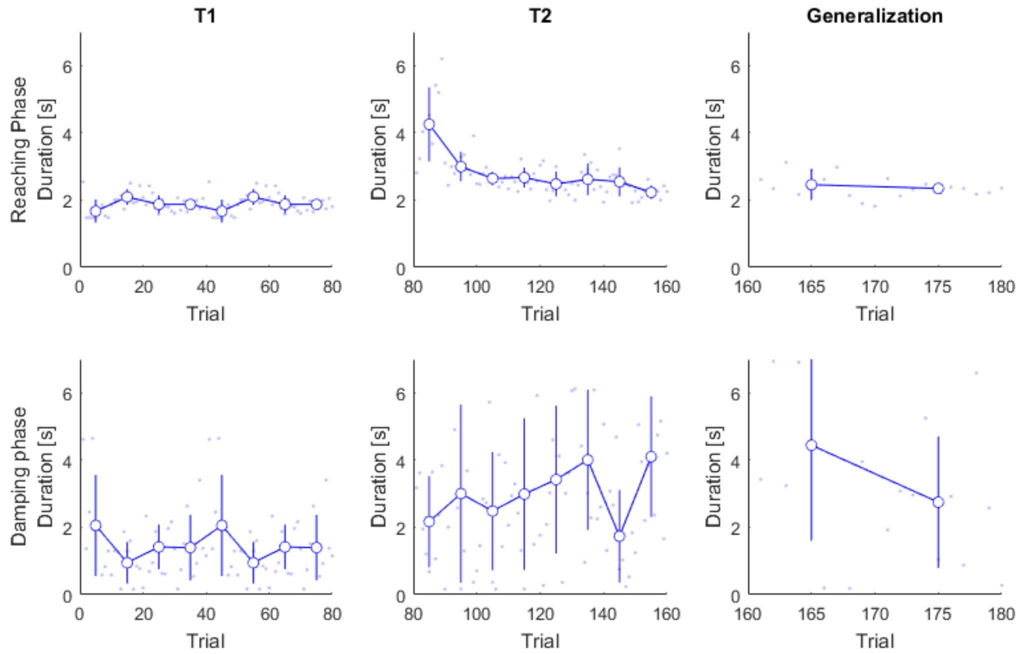

Figure C.5: Movement time of one subject divided into the reaching movement and the damping movement. Subject 1, group 1.

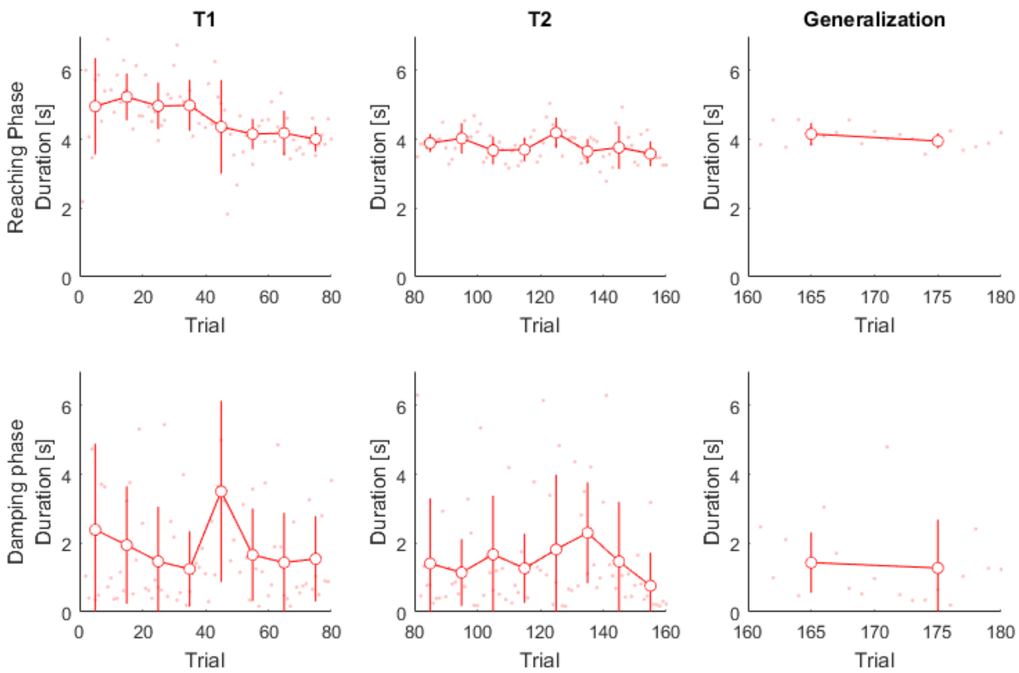

Figure C.6: Movement time of one subject divided into the reaching movement and the damping movement. Subject 2, group 2.

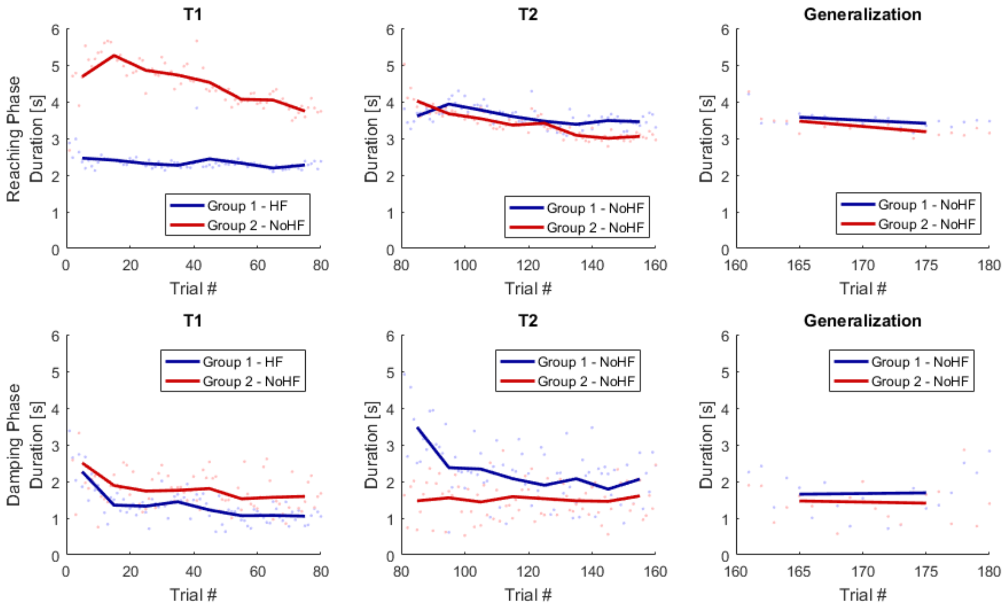

Figure C.7: Movement time of one subject divided into the reaching movement and the damping movement. Subject 2, group 2.

D

Dynamics and Implementation in Simulink

D.1. Mass-Spring-Damper System

Figure D.1 shows a schematic of the simulated mass-spring-damper system. The dynamics properties are listed in table D.1. M_h is the mass of the arm of the subject controlling the teleoperator.

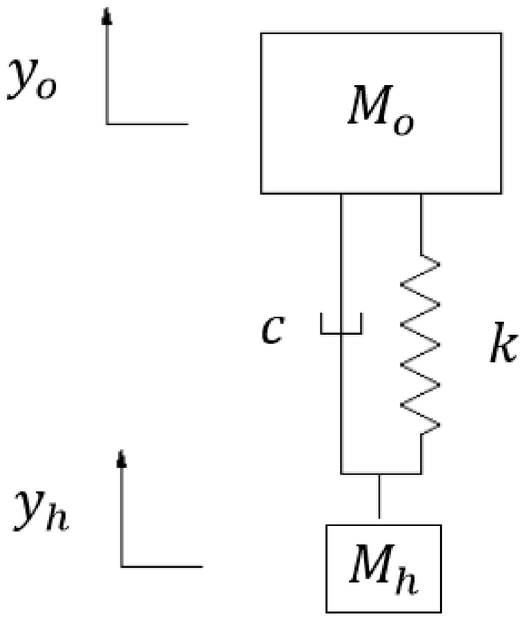

Figure D.1: Schematic of the simulated mass-spring-damper system

D.2. Equations of Motion

The mass-spring-damper system and the hand mass were modelled by the following equations:

$$m_o \ddot{y}_o + c\dot{y}_o + k(y_o - y_h) = 0$$

Table D.1: Overview of the dynamic properties of the virtual mass-spring-damper system

Property	Value
Mass (training phases)	3 [kg]
Stiffness (training phases)	120 [N/m]
Mass (generalization phase)	6 [kg]
Stiffness (generalization phase)	60 [N/m]
Damping	1 [N/m/s]
l_o (initial spring length)	0 [cm]

and

$$m_h \ddot{y_h} = f_h$$

where
m_o = Object mass
m_h = Hand mass
y_o = Object position
y_h = Hand position
c = Damping coefficient
k = Spring constant
f_h = Force, exerted by the hand
The state-space system corresponding to these equations of motion are

$$\begin{bmatrix} \dot{q_1} \\ \dot{q_2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -k/M_0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} + \begin{bmatrix} 0 \\ k/M_0 \end{bmatrix} y_h$$

where $q_1 = x$ and $q_2 = \dot{x}$.

The interaction force, exerted by the spring and the damper due to the displacement of the hand, can then be calculated by

$$F_e = -F_s - F_d$$

$$F_e = -k(y_h - y_o) - c(\dot{y_h} - \dot{y_o})$$

The system assumes an initial spring length of 0 cm, meaning that there is no spring force when the hand and the object are at the same position.

D.3. Simulink

The dynamics of the double mass-spring-damper system, described in section D.2, are implemented in Simulink. This implementation is described in this section.

A graphical user interface (GUI) was used to start and stop the experiment, switch between the groups and phases, and to adjust the dynamics. See figure **??** for an overview of the GUI. The GUI was designed using the GUIDE function in MATLAB.

Upper Level

Figure D.2 shows the upper level of the Simulink model. In green are the inputs and outputs for the model and for the HapticMaster. In blue is the model that calculates the inputs and outputs. As can be seen, the measurements of the HapticMaster are the input. These measurements contain the measured position , velocity and force (y_h, v_h, F_h) of the HapticMaster (controlled by the hand). The model uses this information to calculate the interaction force F_e, as well as the object position and velocity (y_o, v_o). What can be seen, is that the interaction force F_e is only send to the HapticMaster when this is enabled in the model. This can be enabled in the GUI.

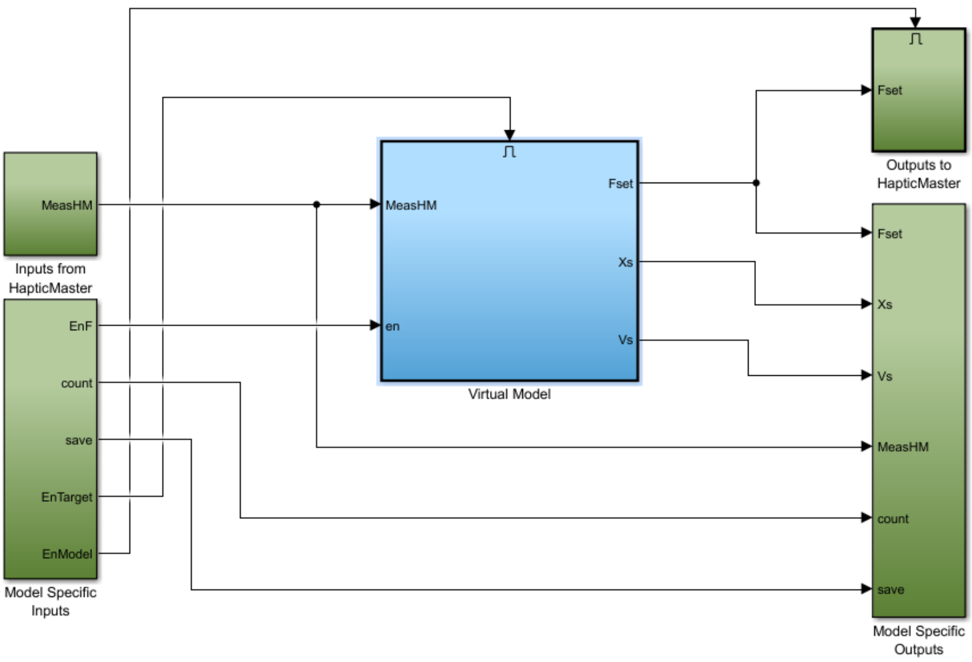

Figure D.2: Top level of the Simulink model.

Lower levels

In the lower levels the slave position and velocity, and the interaction force are calculated using the measurements of the HapticMaster. A schematic of this process is shown in figure D.3. The orange symbols are the inputs, as measured by the HapticMaster. The green symbols are the outputs. X_s is the object position, and F_e is the interaction force that will be send to the HapticMaster (if this mode is enabled). The forces are calculated using the following equations.

$$F_e = -F_(spring) - F_(damp)$$

$$F_(spring) = k(x_m - x_s)$$

$$F_(damp) = c(\dot{x_m} - \dot{x_s})$$

$$F_s = kx_s + c\dot{x_s}$$

$$F_m = kx_m + c\dot{x_m}$$

$$A = F_m - F_s + F_h$$

$$X_s = A/m_s$$

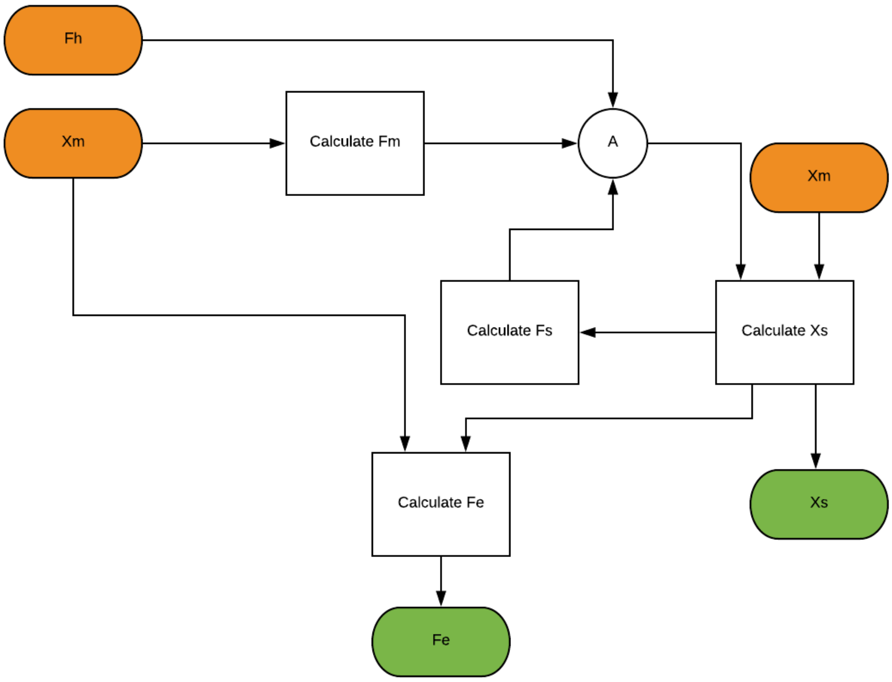

Figure D.3: Lower level of the Simulink Model.

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