The effect of visuohaptic delays on task performance and human control strategy in manual control tasks

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Challenge the future

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The effect of visuohaptic delays on task performance and human control strategy in manual control tasks

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Preface

This master thesis is written as part of my graduation program to achieve a masters degree in Biomedical Engineering. During this masters project I learned what I want to do in the future. Before I entered the field of Biomedical Engineering, I achieved a BSc in Aerospace Engineering. After doing a minor in Biomedical Engineering during my Aerospace Engineering bachelor program, I quickly noticed that I had a great interest in man-machine systems. This led me to the department of Biomedical Engineering, more specifically I chose the specialization Biomechatronics. During my masters program I learned more about man-machine systems. What fascinated me was the potential of haptic technology for various applications, especially related to Virtual Reality (VR). During my internship at Motek Medical (now Motekforce Link) I saw the possibilities of using VR combined with platforms with or without treadmills to create new applications for rehabilitation. VR is still upcoming, but I believe a lot of applications will include VR in the near future. After graduation I hope I can find a job where I can work on these kind of applications.

For those who are interested in specific parts of this thesis, the structure is as follows. The experimental set-up of the inverted pendulum system is described in section 2 Methods. In section 3 Results, the experimental findings are shown. Followed by the discussion in section 4 Discussion. The conclusion and recommendations are given in section 5 Conclusion. Appendix A shows the derivation of the inverted pendulum model. Appendix B shows the information provided to the participants.

Finally I would like to thank my supervisors, Bram Onneweer, Winfred Mugge and Alfred Schouten for giving me countless feedback these past years. Through all the feedback sessions I learned a lot about doing research, showing me a different way of thinking and writing. I am grateful for all their time and effort to help me move forward with my thesis project. I would also like to thank Roel Kuiper for helping me to get started with working on the Bachmann controller and with setting up the inverted pendulum model in Simulink. I want to thank Daan Pool for joining the graduation committee for my graduation presentation and thesis defence. I want to thank my fellow students for their cooperation and teamwork during assignments and projects these past years. Last but not least, I would like to thank my family and friends for their endless love and support.

Andy Cheung

Delft, 8 March 2016

Contents

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Abstract
Currently haptic technology is being widely implemented in applications such as tele-operation. One of the main concerns are the communication delays due to the visual or haptic feedback signals traveling long distances. Also, different subsystems handling visual and haptic feedback cause modality-specific delays causing asynchrony between visual and haptic cues. It is not known how human performance and control strategy is affected by visuohaptic delays during manual control tasks, where humans are continuously controlling and observing a system. In this study an inverted pendulum balancing task served as the manual control task. Participants were required to keep the pendulum upright for 30s with various delays (0, 150, 300ms) in visual and/or haptic feedback provided by a screen and a haptic device (HapticMaster MOOG inc). The task performance was measured in fail rate (amount of failed trials) and RMS θ (root mean square of the pendulum angle measured from the upright position), while human control strategy was evaluated with reversal rate (corrections per second) and RMS $\dot{x}_{hand}$ (root mean square of the hand movement speed of the human operator). The main findings are: 1) adding haptic guidance improves task performance; 2) adding haptic feedback reduces the hand movement speed and the amount of corrections made; 3) Communication delays degrade the task performance more than modality-specific delays; 4) Large delays in haptic guidance feedback evoke an aggressive control strategy. In general adding haptic guidance improves task performance with manual control tasks, however humans adapt an aggressive control strategy when large haptic delays are involved.

Keywords
Inverted pendulum, Visual delay, Haptic delay, Haptic guidance, Human control strategy, Manual control, Human-machine interaction

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Introduction

Haptic technology is becoming more readily accessible and is being widely implemented in the user interface of various modern devices, for example the touchscreen of current smarthphone devices [1]. Applications with traditional joysticks involves proprioceptive and visual feedback. Nowadays with haptic technology, additional sensory information is received through force feedback, which is found in various fields of applications for example in the entertainment industry (e.g. force-feedback joysticks/steering wheels); in training simulators (e.g. Simodont dental trainer MOOG inc.); and in telemanipulation tasks (e.g. space operations, telesurgery).

During manual control tasks humans are continuously controlling and observing a system while receiving sensory feedback through different sensory modalities (e.g. ears, eyes, hands). With haptic shared control, a human operator and a PID controller can simultaneously exert control, in which a PID controller usually controls low-level functions (e.g. reducing oscillation, obstacle avoidance) while the human operator focuses on high-level control (e.g. path planning, position control) [2], [3]. Various studies showed that adding haptic feedback during manual control tasks (e.g. peg-in-hole task during telemanipulation, tissue-instrument contact in telesurgery) improves task performance (e.g. improve accuracy, limit applied forces) [4], [5], [6].

Numerous studies report the benefits of adding haptic technology, however some studies indicate the possible risks of adding haptic feedback, like impede learning (e.g. during rhythmic tasks), deskilling (e.g. car driving), or causing sensory mismatches (e.g. delayed visuals in telesurgery) [7], [8], [9]. Two main types of delays can be distinguished: 1) communication delays (also known as network delays in some applications), where both visual and haptic feedback are delayed with an equal amount; 2) modality-specific delays (also known as asynchrony between sensory modalities), where either visual feedback is delayed more than haptic feedback or vice versa [10] [11]. In some visuohaptic applications relatively large delays (>300ms [7], [12]) might be present (e.g. telesurgery, teleoperations), which can deteriorate performance.

Modality-specific delays can cause a mismatch between visual and haptic sensory feedback as both channels are not synchronized. It is unknown how these sensory mismatches caused by visuohaptic delays influence the task performance during manual control, which leads to the following research question: "What is the effect of visuohaptic delays on human performance in manual control tasks?". The different combinations of visuohaptic delays leads to various sub-questions:

1. When both visual and haptic feedback is provided, and only visual feedback is delayed: will haptic feedback improve task performance?
2. When both visual and haptic feedback is provided, and only haptic feedback is delayed: will haptic feedback degrade task performance?
3. In case when visual feedback is delayed more than haptic feedback: will humans rely more on haptic feedback?
4. Is it better to wait to keep the delays equal (communication delay) or provide the feedback when available (modality-specific delay)?

A well-known manual control task is the inverted pendulum balancing task, which is widely used in various experiments (e.g. understanding human limitations, designing self-balancing systems) [13], [14], [15], [16]. In the inverted pendulum task the human operator has to keep a (virtual) pendulum upright. The pendulum balancing task is essentially an unstable system where continuous human inputs are required to stabilize the system. Next to evaluating human task performance, the inverted pendulum task is used to provide information for identifying human control strategies [17]. The difficulty of the pendulum balancing task is mainly determined by the dynamics of the pendulum (mass and length of the pendulum) and the time delays affecting visual and haptic feedback to the human.

Several studies on balancing the inverted pendulum task have focused on either manual control or automated control, where a PID controller balances the inverted pendulum autonomously (e.g. [18], [19]). Only little research has been done on balancing the inverted pendulum with shared control. So far, haptic feedback or in this case haptic guidance has shown potential to improve task performance by decreasing the pendulum sway when compared to balancing the pendulum without haptic guidance [4]. Although haptic guidance can improve task performance (reduce pendulum sway), the influence of delayed haptic guidance on the task performance or human control strategy is unknown.

The goal of this research is to find the effect of visuohaptic communication and modality-specific delays on task performance and human control strategy with an inverted pendulum balancing task. Where task performance is defined by how well the pendulum is kept upright and where human control strategy is defined by how many corrective movements are made and how fast the corrective movements are performed.

2. Methods

2.1 Participants

Nine subjects participated in this experiment. The participants had no previous knowledge of the experimental set-up and were all right-handed men in the age group ranged from 20 – 30. Each experiment lasted about 120 minutes, no compensation was provided. All participants had normal or corrected-to-normal vision and had no history of neural or movement disorders. Before participating, the subjects signed the informed consent giving permission to use their experimental data anonymously for the purpose of scientific research. The participants were allowed to discontinue their participation at any time. The experiment is approved by the Human Research Ethics Committee (HREC) at Delft University of Technology.

2.2 Experimental set-up

A picture of the experimental set-up is shown in Figure (1). The set-up consists of four subsystems which are connected with a router, see Figure (2). The subsystems used for this inverted pendulum balancing experiment are:

- LED tv-screen (40"): served as visual output device providing visual feedback. The 40" inch Samsung LED tv has a refresh rate of 100 Hz and a resolution of 1920 x 1080 pixels. The size of the pendulum on the screen was approximately 30 cm, which could move approximately 26 cm to the left or right when positioned at the middle of the screen (starting position of the experiment). The distance between the human operator and the tv-screen is approximately 1.5m. 1
- PC: runs Matlab (MathWorks) where the custom made Matlab-scripts creating the pendulum visuals are updated with a frequency of 50 Hz. The PC is also used to create the pendulum model in Simulink (MathWorks). The custom made Simulink model was converted into C-code which was processed by the Bachmann controller for real-time control. The PC also ran SolutionCenter (Bachmann electronic GmbH) to control the experimental variables of the pendulum model with the Bachmann controller. Finally the PC ran a custom made Matlab GUI (graphical user interface) to operate the experiment and log the measured variables.
- Bachmann controller (Bachmann electronic GmbH): enabled real-time control of the custom made

Simulink pendulum model, where the parameters can be adjusted in real-time (using SolutionCenter) with an update frequency of 1000Hz. The interactions (e.g. force in- and output) between the Simulink pendulum model and the HapticMaster are controlled by the Bachmann controller.

- HapticMaster (MOOG inc.): served as the input device and the force output device, providing haptic feedback. As an input device, the applied force of the human operator is measured by the force sensor at the end-effector. As result of the applied force, the corresponding movement of the end-effector is calculated by the HapticMaster. The movement range of the HapticMaster in longitudinal direction is approximately -21cm 21cm, where 0cm indicates the starting position and negative means moving the HapticMaster towards you while positive means moving the HapticMaster away from you when standing in front of the HapticMaster. Based on the measured force, the HapticMaster in combination with the Bachmann controller provides a modelled position, velocity and acceleration as input signals for the Simulink pendulum model.

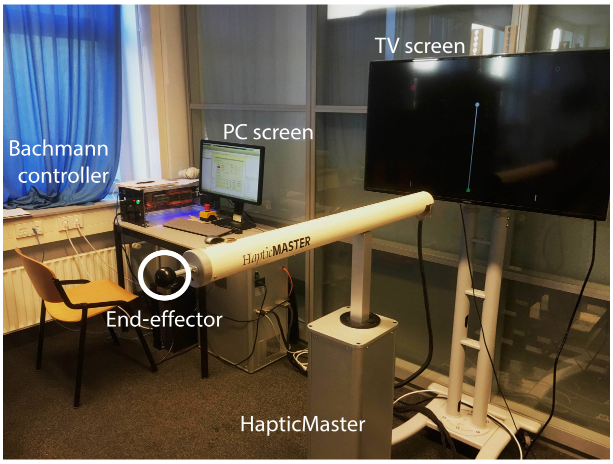

Figure 1. *Picture of the experimental set-up. On the left side of the picture the Bachmann controller and the PC screen are located on a small desk. The PC system is placed underneath the desk next to the electronics box of the HapticMaster. The robotic arm of the HapticMaster is located in the middle of the picture, the end-effector of the HapticMaster is indicated with a white circle. On the right side, the TV screen including the stand is placed.*

2.2.1 Inverted pendulum model

A schematic of the inverted pendulum model is shown in Figure (3). The inverted pendulum system consists of a cart and a pendulum rod. The cart is supported vertically, allowing only horizontal movements. The pendulum rod is fixed on the cart with a hinge, so the pendulum can only rotate around this hinge.

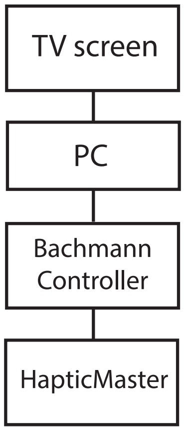

Figure 2. *Schematic overview of the connected subsystems.*

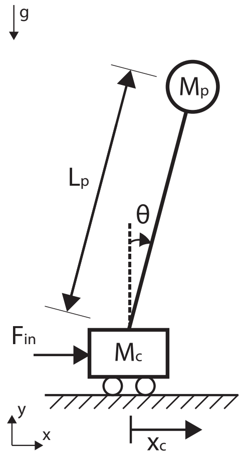

Figure 3. *Schematic of the inverted pendulum on a cart model.*

The model parameters are:

- F_{in} = Input force of human operator
- M_c = Mass of cart
- M_p = Mass of pendulum
- L_p = Length of pendulum rod
- g = Gravitational acceleration

The system signals are given by:

- x_c = Position of cart
- θ = Angle of pendulum

The inverted pendulum system can be described by two equations, Equation (1) describes the cart dynamics and Equation (2) describes the pendulum dynamics (derivation see Appendix A).

$$F_{in} = \overbrace{\ddot{x}_c(M_c + M_p)}^{inertia} + \overbrace{b\dot{x}_c}^{friction} + \overbrace{M_pL_p\ddot{\theta}\cos(\theta)}^{tangential force} - \underbrace{M_pL_p\dot{\theta}^2\sin(\theta)}_{centripetal force} \quad (1)$$

$$\overbrace{M_pL_p^2\ddot{\theta}}^{inertia} + \overbrace{M_pL_pg\sin(\theta)}^{gravity} = \overbrace{-M_pL_p\ddot{x}_c\cos(\theta)}^{cart\ \ effect} \quad (2)$$

For the calculation of the cart dynamics, the effect of the pendulum on the cart is included by taking into account the tangential and centripetal forces. The joint between the cart and pendulum is assumed to be a frictionless joint, also it is assumed that there is no air friction. Only the cart is damped by means of ground friction.

2.2.2 Haptic guidance forces

The inverted pendulum model gives two main outputs, the pendulum angle θ and the cart position x_c. A Proportional-Integral-Derivative (PID) controller was designed to keep the inverted pendulum upright automatically and to keep the cart position at 0, which is in the middle of the screen. Two PID controllers are used: the pendulum PID, tries to keep the pendulum upright by moving the cart towards a calculated optimal position (Figure (4) case 1); the cart PID, tries to move the cart slowly back to the initial position as much as possible (Figure (4) case 2).

Combining the calculated force of both PID controllers gives a resultant force, which moves the cart either to the left or to the right. The resultant force is used as a force output to the HapticMaster which moves the end-effector with this resultant force. The provided haptic guidance forces range from approximately -5N to +5N.

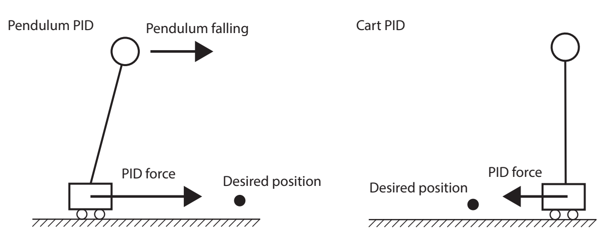

Figure 4. *Schematic of how the two PID controllers work. Case 1 (left): PID force moves the cart to the desired location to balance the pendulum. Case 2 (right): PID force moves the cart to the middle of the screen defined as the starting point.*

2.2.3 Implementation

The inverted pendulum model and the haptic guidance forces from the PID controllers were implemented in a Simulink model, which regulates all the in- and output signals. In Simulink the in- and output signals are easily manipulated, so time delays were introduced by adding a unit delay block with a given time duration at the output signal.

During the experiments the human operators (participants) held the end-effector (see Figure (1)) of the HapticMaster. When the human operator moved the end-effector towards or away from him, the corresponding force was measured which was used as the force input in the Simulink model. The Simulink model calculated the pendulum state outputs, which were shown on the screen see Figure (5). Also, the pendulum state outputs were used to calculate the guidance force. An overview of the human operator interacting with the HapticMaster including the Simulink in- and outputs is shown in Figure (6).

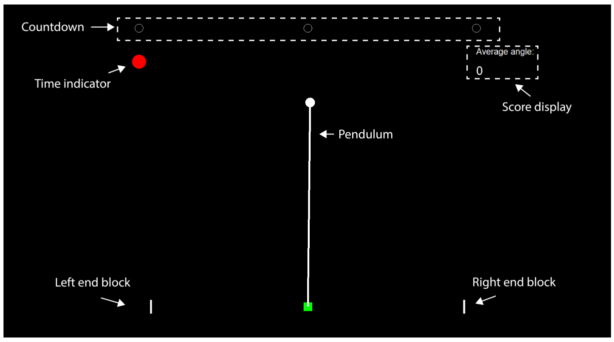

Figure 5. *Description of the elements shown on the tv-screen during the experiment. The countdown indicator gave the start sign of a trial. A time indicator which changed from red to cyan showing that a trial has been completed (30s elapsed). The average angle only appeared when the trial ended, which gave the participants some feedback on how they performed that trial. The left and right end blocks show the maximum movement range of the pendulum cart (or how far the HapticMaster could move in real life). In the middle of the screen the pendulum system is shown, showing the pendulum cart, the pendulum rod and mass.*

2.3 Procedures

Participants received the task instructions, which in short mentioned that the task is to keep the pendulum upright for 30 seconds by moving the end effector of the HapticMaster, while trying to keep the deviations from the upright position as small as possible. The complete task instructions provided to the participants can be found in Appendix B.

After reading the instructions the participants were familiarized with the experimental set-up by practicing 5 minutes with the three visual delay conditions (0, 150, 300ms visual delay) without haptic guidance. This was followed by practicing another 5 minutes with haptic guidance with the three haptic delay conditions (0, 150, 300ms haptic delay), while visual delay was set to 0ms.

After familiarizing with the experimental set-up, participants received additional instructions noting that both visual feedback and haptic feedback can be delayed. The experiment consisted of 12 different conditions, 3 with only visual feedback and 9 with visual and haptic feedback presented in a random order (incomplete counterbalanced). In each condition either visual and/or haptic feedback was delayed with 0ms, 150ms or 300ms, see Figure (7) for an overview of all conditions.

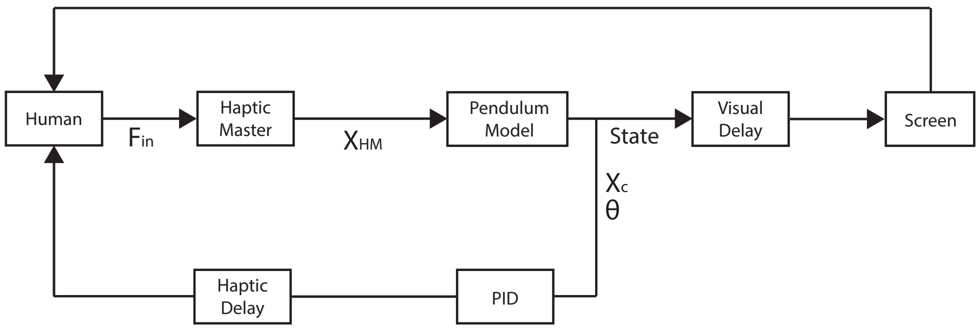

Figure 6. *A schematic overview of the main components of the Simulink model. The human exerts a force on the end-effector of the HapticMaster, which calculates the corresponding movement. The pendulum model used this movement to calculate the pendulum states. The pendulum states are delayed with a given amount depending on the experimental condition before shown on the screen (visual delay). The PID controller uses the pendulum states to calculate a guidance force moving the end-effector of the HapticMaster towards the calculated optimal position to balance the inverted pendulum. This guidance force are be delayed with a given amount depending on the experimental condition (haptic delay).*

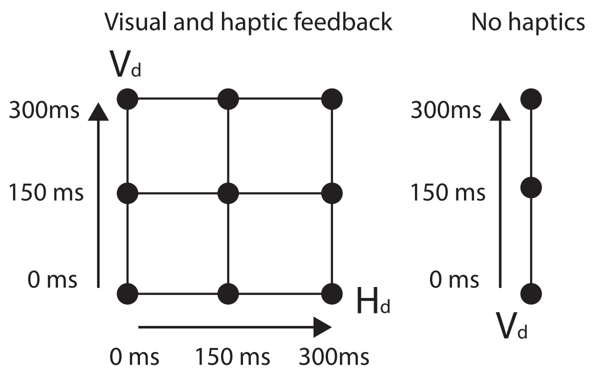

Figure 7. *Overview of the 12 experimental conditions. The nine visuohaptic delay conditions are shown on the left side, where either visual and/or haptic feedback is delayed with 0, 150 or 300ms. The three visual delay conditions without haptic guidance are shown on the right.*

During the experiment 5 practice trials were performed at the start of a random experimental condition to let the participants train with the delayed visual and/or haptic feedback. Afterwards 5 trials were recorded, so in total 5 practice trials were performed and 5 trials were measured for each condition, resulting in 2 (practice and measurement) x 5 (trials) x 12 (conditions) = 120 trials per participant. The participants were also instructed to hold the end-effector of the HapticMaster during a trial until the trial was completed (balanced for 30s) or until the trial failed (pendulum falls below the horizontal line).

2.3.1 Data analysis

To evaluate the human performance, the amount of trials that have not been completed was counted. The amount of fails is expressed as a fail rate in a percentage. This was calculated as follows:

$$\text{Fail Rate} = \frac{\text{failed trials}}{\text{total amount of trials}} \cdot 100\% \qquad (3)$$

Another way to evaluate the human performance is to calculate the deviation of the pendulum angle from the upright position.The root-mean-square (RMS) is used to obtain the performance score for each trial. The RMS angle was calculated as follows:

$$\text{RMS } \theta = \sqrt{mean(\theta^2)} \qquad (4)$$

The result of Equation (4) gives the score for one trial, where θ is the recorded signal of the pendulum angle measured from the upright position.

Human control strategy is evaluated with the reversal rate and the hand movement speed of the human operator. Reversal rate is defined as the amount of sign changes (switching from a positive to a negative value and vice versa) of x_{hand}, which indicates how often the hand of the human operator changes direction per second. The reversal rate was calculated as follows:

$$\text{Reversal Rate} = \frac{\text{Amount of reversals}}{\text{Task duration}} \qquad (5)$$

The hand movement speed indicates how fast the human operator moved during a trial. The RMS is used to obtain the hand movement speed value of a trial, which was calculated as follows:

$$\text{RMS } \dot{x}_{hand} = \sqrt{mean(\dot{x}_{hand}^2)} \qquad (6)$$

In Equation (6) $\dot{x}_{hand}$ is the recorded signal of the hand movement speed of the operator.

2.3.2 Statistical Analysis

The four metrics were tested with repeated measures ANOVA with significance level .05. Two tests were performed per metric, where test 1 focused on the effect of adding haptic guidance and where test 2 focused on the effect of visuohaptic delays. The two tests are:

- Test 1: Compares the visual delay conditions without haptic guidance (V0, V150, V300) with the visual delay conditions with haptic guidance (V0H0, V150H0, V300H0), where the conditions are shown in Figure (7).
- Test 2: Compares the nine different combinations of visuohaptic delays (V0H0, V150H0, V300H0, V0H150, V150H150, V300H150, V0H300, V150H300, V300H300), where the conditions are shown in Figure (7).

3. Results

3.1 Test 1: The effect of added haptic guidance

The haptic guidance conditions without haptic delay (V0H0, V150H0, V300H0) were compared with the no haptic guidance conditions (V0, V150, V300). Adding haptic guidance showed a significant effect on task performance (fail rate and RMS θ) and on human control strategy (reversal rate and RMS $\dot{x}_{hand}$).

3.1.1 Task performance

Increasing the visual delays significantly increased the fail rate ($p < .05$). Post-hoc tests on the visual delay conditions revealed that each step (0ms to 150ms, 0ms to 300ms, 150ms to 300ms) significantly increased the fail rate ($p < .05$).

Adding haptic guidance significantly reduced the fail rate ($p < .05$). Figure (8) shows that the fail rate in conditions V0H0 and V150H0 is 0% in test 1, meaning that haptic guidance helped the human operators to complete all trials with 0ms and 150ms visual delay, while without haptic guidance the fail rate was higher for both 0ms and 150ms (V0 and V150) ($p < .05$). The difference in fail rate is even more clear when visual delay was increased to 300ms (V300 vs V300H0) ($p < .05$).

The lower the RMS θ, shown in Figure (9), the closer the pendulum was kept near the upright position. Increasing the visual delay significantly increased the RMS θ ($p < .05$), which showed that with larger visual delays the pendulum swayed more from the upright position. Post-hoc tests on the visual delay conditions revealed that increasing the visual delays (0ms to 150ms, 0ms to 300ms, 150ms to 300ms) significantly increased the RMS θ ($p < .05$).

Adding haptic guidance decreased the RMS θ significantly ($p < .05$). The RMS θ of the three conditions with haptic guidance (V0H0, V150H0, V300H0) was smaller than the RMS θ of the three conditions without haptic guidance (V0, V150, V300) ($p < .05$).

In summary, increasing visual delays in test 1 degraded task performance by increasing fail rate and increasing RMS θ, while adding haptic guidance improved task performance by reducing fail rate and reducing RMS θ, especially when large visual delays (300ms) were present.

3.1.2 Human control strategy

The higher the reversal rate the more corrections the human operator made during a trial. Increasing the visual delay significantly decreased the amount of reversals made ($p < .05$), which means that less corrections or actions were made when visual delays became larger as is shown in Figure (10). Post-hoc tests on the visual delay conditions revealed that increasing the delay from 0ms to 300ms shows a significant decrease in reversal rate ($p < .05$).

Adding haptic guidance significantly decreased the reversal rate ($p < .05$). For all three visual delays (0ms, 150ms and 300ms) less corrections were made with haptic guidance compared to without haptic guidance ($p < .05$).

The RMS $\dot{x}_{hand}$ indicates how fast the hand of the human operator moved during a trial, which is shown in Figure (11). With increasing visual delays the RMS $\dot{x}_{hand}$ significantly increased ($p < .05$), meaning that faster movements were made. Post-hoc tests on the visual delay conditions revealed that increasing the delay from 0ms to 150ms or from 0ms to 300ms shows a significant decrease in RMS $\dot{x}_{hand}$ ($p < .05$).

Adding haptic guidance significantly decreased RMS $\dot{x}_{hand}$ ($p < .05$). The hand movement speed decreased for all three visual delay conditions with haptic guidance compared to without haptic guidance ($p < .05$).

In short, both increasing visual delays and adding haptic guidance in test 1 influenced human control strategy. Increasing visual delays reduced the reversal rate and increased the RMS $\dot{x}_{hand}$ (less corrections, faster movements), while adding haptic guidance reduced the reversal rate and decreased the RMS $\dot{x}_{hand}$ (less corrections, slower movements).

3.2 Test 2: The effect of visuohaptic delays

The nine visuohaptic delay conditions (V0H0, V150H0, V300H0, V0H150, V150H150, V300H150, V0H300, V150H300, V300H300) were compared with test 2, which showed that visuohaptic delays have an effect on task performance, while only haptic delays have an effect on human control strategy.

3.2.1 Task performance

Increasing visuohaptic delays significantly increased the fail rate (both visual delays and haptic delays, $p < .05$), which is shown in Figure (8). No interaction effects of visual and haptic delays were found ($p = .24$).

Post-hoc tests on the haptic delay conditions revealed a significant increase in fail rate ($p < .05$) when haptic delay was increased from 0ms to 300ms. On the other hand, post-hoc tests on the visual delay conditions revealed no significant effect of modality-specific delays (when $V_d \pm H_d$). The highest fail rate is at 300ms communication delay (when $V_d = H_d$).

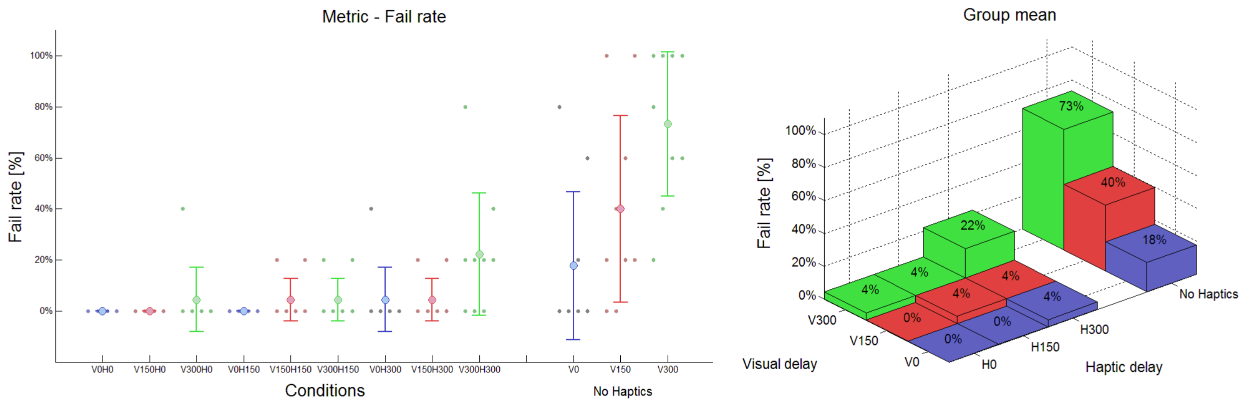

Figure 8. *The fail rate, shown in percentage. In the left figure: the nine conditions on the left are the visuohaptic conditions. The three conditions on the right are the visual conditions without haptic guidance. The smaller dots indicate the mean fail rate of a single subject averaged over 5 trials (to keep the figure clear, only 4 dots at a certain fail rate are shown next to each other). The larger dots indicate the mean fail rate of the group of 9 participants. The errorbars indicate ± 1 standard deviation (SD) of the fail rate of the group of 9 participants. In the right figure: a 3D overview of the means of the 12 conditions is shown, where visual and haptic delay conditions are distinguished more clearly. In the 3D view the errorbars are omitted for clarity reasons. The 3D view follows the same pattern as the conditions overview in Figure (7).*

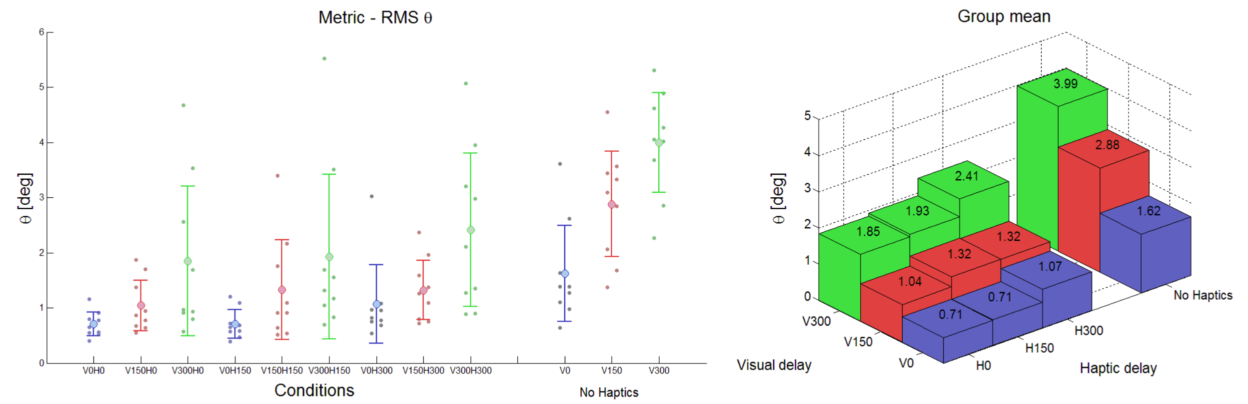

Figure 9. *The root mean square (RMS) of the angle of the pendulum (θ), shown in degrees. In the left figure: the nine conditions on the left are the visuohaptic conditions. The three conditions on the right are the visual conditions without haptic guidance. The smaller dots indicate the mean RMS θ of a single subject averaged over 5 trials. The larger dots indicate the mean RMS θ of the group of 9 participants. The errorbars indicate ± 1 standard deviation (SD) of the RMS θ of the group of 9 partcipants. On the right: a 3D overview of the means of the 12 conditions is shown, where visual and haptic delay conditions are distinguished more clearly. In the 3D view the errorbars are omitted for clarity reasons. The 3D view follows the same pattern as the conditions overview in Figure (7).*

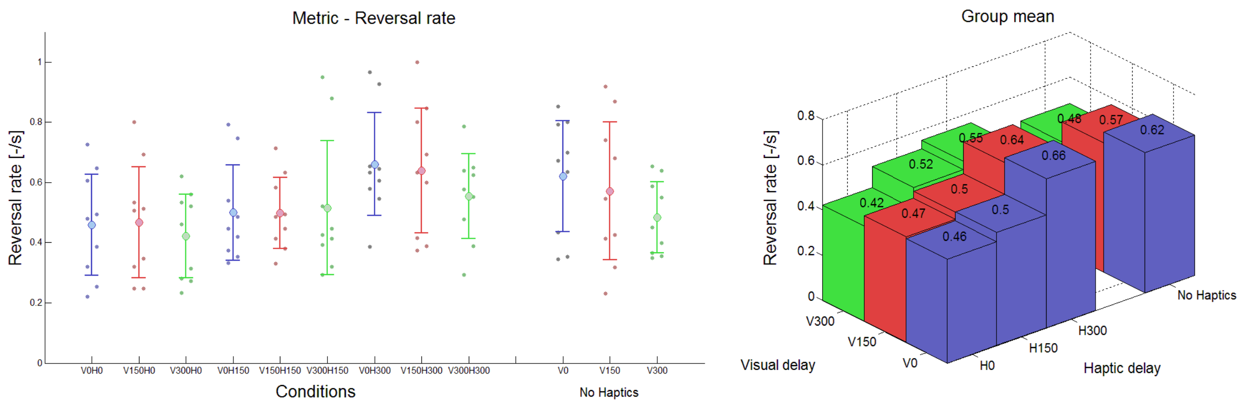

Figure 10. *The reversal rate of the human operator input, shown as sign changes of the hand of the operator (switching from a positive to a negative value and vice versa) per second. In the left figure: the nine conditions on the left are the visuohaptic conditions. The three conditions on the right are the visual conditions without haptic guidance. The smaller dots indicate the mean reversal rate of a single subject averaged over 5 trials. The larger dots indicate the mean reversal rate of the group of 9 participants. The errorbars indicate ± 1 standard deviation (SD) of the reversal rate of the group of 9 partcipants. In the right figure: a 3D overview of the means of the 12 conditions is shown, where visual and haptic delay conditions are distinguished more clearly. In the 3D view the errorbars are omitted for clarity reasons. The 3D view follows the same pattern as the conditions overview in Figure (7).*

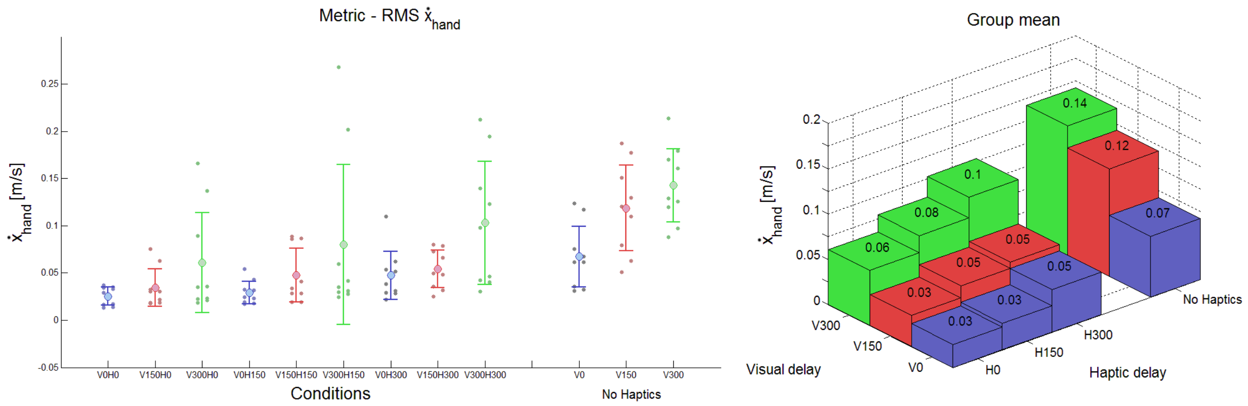

Figure 11. *The root mean square (RMS) of the hand movement speed ($\dot{x}_{hand}$) of the human operator, shown in meters per second. In the left figure: the nine conditions on the left are the visuohaptic conditions. The three conditions on the right are the visual conditions without haptic guidance. The smaller dots indicate the mean RMS $\dot{x}_{hand}$ of a single subject averaged over 5 trials. The larger dots indicate the mean RMS $\dot{x}_{hand}$ of the group of 9 participants. The errorbars indicate ± 1 standard deviation (SD) of the RMS $\dot{x}_{hand}$ of the group of 9 partcipants. In the right figure: a 3D overview of the means of the 12 conditions is shown, where visual and haptic delay conditions are distinguished more clearly. In the 3D view the errorbars are omitted for clarity reasons. The 3D view follows the same pattern as the conditions overview in Figure (7).*

Increasing visuohaptic delays significantly decreased (for both visual delays and haptic delays) the RMS θ ($p < .05$), which is shown in Figure (9). No interaction effects of visual and haptic delays were found ($p = .52$).

Post-hoc tests on the visual delay conditions revealed a significant increase in RMS θ ($p < .05$) when visual delay was increased from 0ms to 150ms. Post-hoc test on the haptic delay conditions revealed no significant effect.

To sum it up, both increasing visual and haptic delays in test 2 degraded task performance shown by an increase in fail rate and an increase in RMS θ. With modality-specific delays the fail rate remained small (up to 4%) even at 300ms, while with communication delay the fail rate was larger than with modality-specific delays especially when the presented visuohaptic delay was 300ms (up to 22%).

3.2.2 Human control strategy

No significant effect on reversal rate, shown in Figure (10), was found with increasing visual delay ($p = .420$). Increasing haptic delays significantly increased the reversal rate ($p < .05$). No interaction effects of visual and haptic delays were found ($p = .35$). Only haptic delays had an effect on human control strategy by increasing the reversal rate when haptic delay was increased.

Increasing visual delays had no significant effect ($p = .061$) on RMS $\dot{x}_{hand}$, which is shown in Figure (11). Increasing haptic delays significantly increased the RMS $\dot{x}_{hand}$ ($p < .05$). Post-hoc tests on haptic delay conditions revealed that RMS $\dot{x}_{hand}$ significantly increased when the haptic delay was increased from 0ms (V0H0) to 300ms (V0H300). Haptic delays affected the human control strategy by increasing the hand movement speed when haptic delay was increased.

In summary, the reversal rate and RMS $\dot{x}_{hand}$ results of test 2 showed that only delayed haptic feedback had an effect on human control strategy by increasing the reversal rate and increasing the hand movement speed when haptic delay was increased.

4. Discussion

4.1 The effect of added haptic guidance feedback

The pendulum balancing task is an unstable task, which requires continuous corrections from the human operator to keep the pendulum upright. The PID controller acts as haptic guidance to help human operators correct when the pendulum deviates from the upright position.

First of all, test 1 showed that visual delays makes the task more difficult, which is shown by a decrease in task performance measured in increased fail rate and increased RMS θ. Both metrics show that the task performance degrades with increasing visual delays in the absence of haptic guidance. In terms of human control strategy, visual delays affect the strategy by decreasing the reversal rate with increasing visual delays. In the absence of haptic guidance, the decreased reversal rate is compensated by an increase in hand movement speed as is shown by an increase in RMS $\dot{x}_{hand}$ when visual delays become larger. With increasing visual delays, human operators move faster but more intermittently (less corrections made per timespan with higher movement speed). The fast intermittent strategy in combination with large visual delays (delayed response of the human operator) will probably lead to a higher chance to overshoot the upright position, which explains an increase in RMS θ and a higher chance of failing a trial.

Secondly, test 1 showed that haptic guidance helps improve the task performance, by decreasing the fail rate and the RMS θ. The effect of adding haptic guidance is even more noticeable when visual delays are large, which was shown by the fail rate and RMS θ results. The PID controller responsible for the haptic guidance forces was designed to react aggressively such that it corrects directly when the pendulum deviates from the upright position. Normally, human operators initiate their correcting movement later with large visual delays, because they need to react based on their received visual feedback. Although the haptic guidance forces are small (< 5N), the guidance force pushes or pulls the human operator towards the desired position, thus initiating the correcting movement directly. Therefore adding haptic guidance has a greater impact when visual delays (150ms and 300ms) are present (fail rate: 40% -> 0% and 73% -> 4% respectively) compared to when no visual delays are present, where humans are still able to correct quickly without the help of haptic guidance (fail rate: 18% -> 0%).

Finally, test 1 showed that haptic guidance affects the human control strategy. Adding haptic guidance decreases the reversal rate and the RMS $\dot{x}_{hand}$, meaning that less and slower correcting movements were made. Both increasing the visual delays and adding haptic guidance decreased reversal rate. However, increasing visual delays led to faster movements while adding haptic feedback resulted in slower movements. With increasing visual delays, the lower reversal rate is mainly because humans make less corrections as they cannot react directy resulting in an intermittent strategy. The lower reversal rate when haptic guidance is added is mainly because the guidance forces kept the pendulum near the upright position, so less corrections were sufficient which is shown by the RMS θ results (for example at V300H0: 1.85deg compared with V300: 3.99deg). So increasing the visual delays tends towards a fast intermittent control strategy, while adding haptic guidance results in a slower movement speed with less corrections made.

4.2 The effect of visuohaptic delays

We showed that adding haptic guidance to a visiomotor task has an effect on both task performance and human control strategy. Here we discuss the effect of delayed haptic guidance and delayed visual feedback on the task performance and human control strategy.

Increasing visual delays or haptic delays degrades task performance by increasing the fail rate and increasing the RMS θ (main effect test 2). Modality-specific delays, where only visual or haptic feedback is delayed, show a small increase in fail rates even when visual or haptic delay reaches 300ms. In Figure (8) delays larger than 150ms (up to 300ms) do not increase the fail rate, when only visual or haptic feedback is delayed (modality-specific delays) as was revealed by post-hoc tests. Although the fail rate did not increase with modality-specific delays, the overall task performance did decrease as the RMS θ increased, shown in Figure (9). Communication delays, where both visual and haptic feedback are delayed with an equal amount, show a larger increase in fail rate and RMS θ when the delays are larger (0-150ms vs 150-300ms). In summary, human operators have little trouble balancing the inverted pendulum task with modality-specific delays. Although the overall task performance degrades with increasing modality-specific delays, the fail rate does not increase. With communication delays, a delay up to 150ms shows no clear decrease in task performance. The worst performance is when a communication delay of 300ms is presented to the human operator which was the largest visuohaptic delay we investigated.

Regarding human control strategy, test 2 showed that only increasing haptic delays affects the control strategy by increasing the reversal rate and by increasing the hand movement speed. Test 1 showed that adding haptic guidance decreased the reversal rate and RMS $\dot{x}_{hand}$, which indicates that humans move slower and make less corrections. Test 2 showed that increasing haptic delays increased reversal rate and RMS $\dot{x}_{hand}$, which indicates that humans adapt a more aggressive control strategy (more corrections made per timespan with higher movement speed).

5. Conclusion

The most important findings are:

- Adding haptic guidance improves task performance by decreasing fail rate and RMS θ
- Adding haptic guidance affects the human control strategy by reducing the movement speed and reducing the amount of corrections made per timespan
- Communication delays, i.e. equal visual and haptic delay, degrade the task performance (fail rate and RMS θ) more than modality-specific delays, i.e. visual and haptic delay are not equal.
- Large delays in haptic guidance feedback evoke an aggressive control strategy as the reversal rate and RMS $\dot{x}_{hand}$ increase

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Appendix A

This appendix shows the derivation of the inverted pendulum model and the tuning of the PID controllers.

Equations of motion

A schematic of the inverted pendulum model is shown in Figure (12). First the inverted pendulum equations describing the system dynamics are derived. The inverted pendulum system consists of a pendulum, which is mounted on a cart with a hinge connection allowing the pendulum to rotate freely around this hinge. The cart is supported in y-direction (vertical) but it can move freely in x-direction (horizontal).

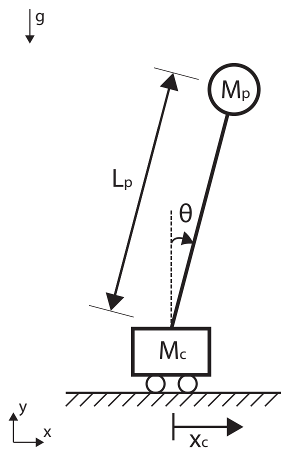

Figure 12. Schematic of the inverted pendulum on a cart model.

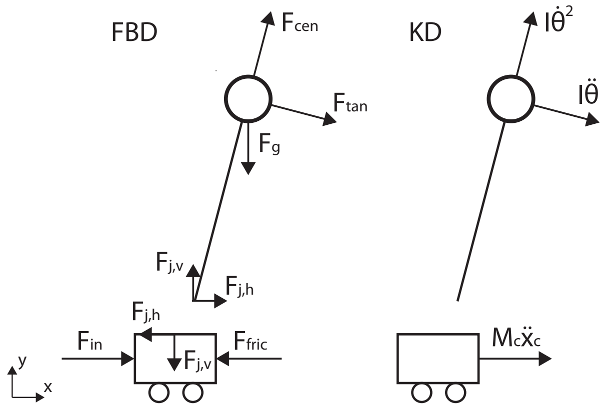

Figure 13. Free body diagram and kinematic diagram of the inverted pendulum model.

Set-up of the inverted pendulum model

The model parameters are:

- M_c = Mass of cart
- M_p = Mass of pendulum
- L_p = Length of pendulum rod
- g = Gravitational acceleration

The system signals are given by:

- x_c = Position of cart
- θ = Angle of pendulum

A free body diagram and a kinematic diagram is shown in Figure (13). The forces acting on the cart are:

- F_{in} = Input force
- F_{fric} = Friction force

The forces acting on both the cart as well as on the pendulum are:

- $F_{j,h}$ = Horizontal joint force
- $F_{j,v}$ = Vertical joint force

The forces acting on the pendulum are:

- F_g = Gravity force
- F_{cen} = Centripetal force
- F_{tan} = Tangential force

The following assumptions are made to derive the pendulum model equations:

- Constant gravity field of 9.81 m/s^2
- No air friction
- Frictionless joint between cart and pendulum
- Massless pendulum rod

Dynamics of the cart

Force balance in x-direction for the cart:

$$\overset{+}{\rightarrow} \sum F_x \Rightarrow F_{in} - F_{j,h} - F_{fric} = M_c \ddot{x}_c \tag{7}$$

The friction force, F_{fric}, depends on a frictional constant, b, and the cart velocity, $\dot{x}_c$:

$$F_{fric} = b\dot{x}_c \tag{8}$$

So Equation (7) can be rewritten in the form:

$$F_{in} = F_{j,h} + b\dot{x}_c + M_c \ddot{x}_c \tag{9}$$

Force balance in x-direction for the pendulum:

$$\overset{+}{\rightarrow} \sum F_x \Rightarrow F_{j,h} - F_{tan}\cos(\theta) + F_{cen}\sin(\theta) = M_p \ddot{x}_c \tag{10}$$

In Equation (10), two forces acting on the pendulum are included, F_{tan} and F_{cen} which are defined as the tangential force and the centripetal force respectively. The tangential force is defined by:

$$F_{tan} = \frac{I_p \ddot{\theta}}{L_p} \tag{11}$$

The pendulum is modelled as a point mass so the moment of inertia of the pendulum is given by:

$$I_p = M_p L_p^2 \tag{12}$$

So the tangential force of the pendulum can be written as:

$$F_{tan} = M_p L_p \ddot{\theta} \tag{13}$$

The centripetal force is defined by:

$$F_{cen} = \frac{I_p \dot{\theta}^2}{L_p} \tag{14}$$

Filling in the moment of inertia of the pendulum results in:

$$F_{cen} = M_p L_p \dot{\theta}^2 \tag{15}$$

Equation (10) can be rewritten as:

$$F_{j,h} = M_p \ddot{x}_c + M_p L_p \ddot{\theta}\cos(\theta) - M_p L_p \dot{\theta}^2 \sin(\theta) \tag{16}$$

Finally combining Equation (9) and Equation (16) results in the equation describing the cart dynamics:

$$F_{in} = \overbrace{\ddot{x}_c(M_c + M_p)}^{inertia} + \overbrace{b\dot{x}_c}^{friction} + \overbrace{M_p L_p \ddot{\theta}\cos(\theta)}^{tangential force} - \overbrace{M_p L_p \dot{\theta}^2 \sin(\theta)}^{centripetal force} \tag{17}$$

Dynamics of the pendulum

Force balance in direction perpendicular to the pendulum:

$$\overset{+}{\searrow} \sum F_\perp \Rightarrow -F_{j,v_\perp} + F_{j,h_\perp} + F_{g_\perp} + F_{tan} = M_p \ddot{x_c}_\perp \tag{18}$$

Rewriting the perpendicular components results in:

$$\begin{aligned} F_{j,v}\sin(\theta) + F_{j,h}\cos(\theta) - M_p g \sin(\theta) - M_p L_p \ddot{\theta} \\ = M_p \ddot{x}_c \cos(\theta) \end{aligned} \tag{19}$$

Torque balance about the centroid of the pendulum:

$$\overset{+}{\circlearrowleft} \sum T_p \Rightarrow -F_{j,v_\perp} L_p + F_{j,h_\perp} L_p = I_{rod} \ddot{\theta} \tag{20}$$

Rewrite:

$$F_{j,v} L_p \sin(\theta) = -F_{j,h} L_p \cos(\theta) - I_{rod}\ddot{\theta} \tag{21}$$

Finally multiplying Equation (19) with L_p and insert Equation (21) results in the equation describing the pendulum dynamics:

$$-F_{j,h} L_p \cos(\theta) - I_{rod}\ddot{\theta} + F_{j,h} L_p \cos(\theta) - M_p L_p g \sin(\theta) - M_p L_p^2 \ddot{\theta} = M_p L_p \ddot{x}_c \cos(\theta) \tag{22}$$

The pendulum is modelled as a mass point on a massless rod, so I_{rod} is 0, thus the equation becomes:

$$\overbrace{M_p L_p^2 \ddot{\theta}}^{inertia} + \overbrace{M_p L_p g \sin(\theta)}^{gravity} = -\overbrace{M_p L_p \ddot{x}_c \cos(\theta)}^{cart} \tag{23}$$

The pendulum parameters were chosen such that the condition with no visual delay without haptic guidance could be completed by multiple pilot participants:

- M_c = Mass of cart = 0.05 [kg]
- M_p = Mass of pendulum = 0.5 [kg]
- L_p = Length of pendulum rod = 6 [m]
- b = frictional constant = 1 [-]

PID control

The PID controller was tuned such that it kept the pendulum in an upright position and the cart position at 0 (the starting position) as much as possible. The Ziegler-Nichols method resulted in a first estimate of tuned parameters which were able to balance the pendulum and keep the cart near the starting position. Using a pendulum simulation the response of the pendulum system was improved. The pendulum PID parameter K_d was increased to decrease the rise time and the PID parameter K_i was increased to decrease the steade-state error.

Finally the simulated parameters were implemented in the experimental set-up and tuned one more time during real-time control. The resulting experimental PID parameters are shown in table 1.

Table 1. PID parameters tuning

Ziegler-Nichols tuning	Kp	Ki	Kd
Pendulum	24	8	18
Cart	-0.11	-0.01	-0.22
Simulation tuning	Kp	Ki	Kd
Pendulum	50	15	18
Cart	-2	-	-4
Experimental tuning	Kp	Ki	Kd
Pendulum	450	135	162
Cart	-6	-	-12

Appendix B

This appendix shows the task instructions the participants received before starting the experiment.

Objective

The goal of this research is to investigate the influence of visuohaptic delays on human performance.

Task instructions:

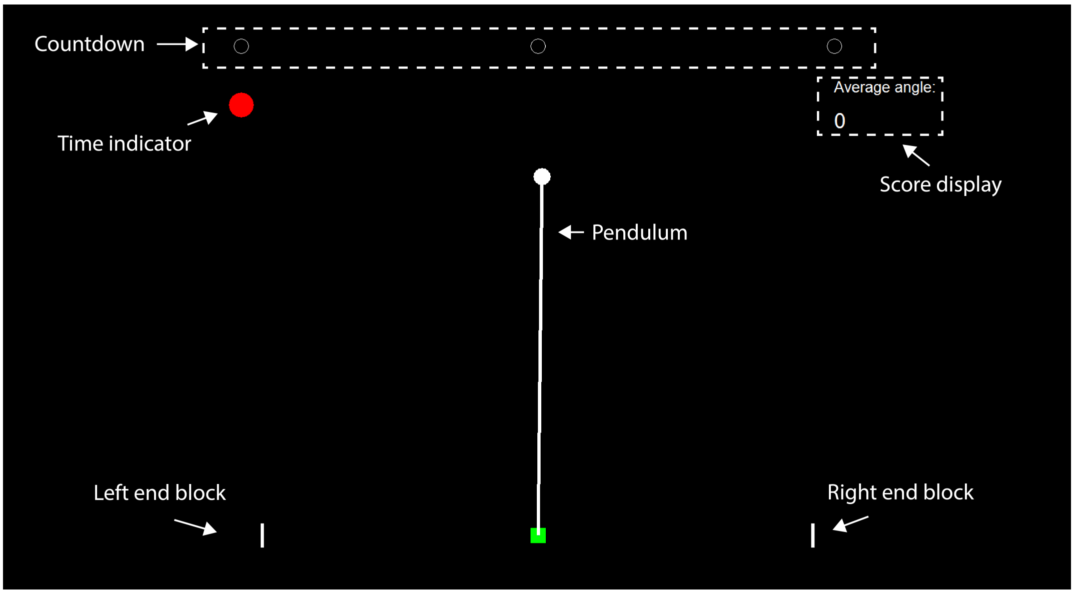

Figure 14. The different elements on the screen indicated with arrows.

Your task is to keep the pendulum upright for 30 seconds by moving the end-effector Figure (15) of the haptic device. Try to keep the deviations from the upright position as small as possible and mind the limited movement range, which is indicated by the white blocks at the left and right ends shown on screen (see Figure 1). Mind that moving the end-effector forward (away from you) moves the pendulum to the left, and moving the end-effector backwards (towards you) moves the pendulum to the right. You will have a chance to practice with these movements during the training sessions.

During the experiment 12 different conditions will be presented, 3 conditions with only visual feedback and 9 conditions with visual and haptic feedback, where both visual feedback and haptic feedback can be delayed. For each condition you will get 5 training trials to familiarize with the presented delay(s). After the training trials you will be asked to judge whether visual/haptic/both were delayed. Then 5 trials are recorded, where your performance is measured by your average deviation from the upright position. Your average deflection will be shown at the top right corner at the end of every trial.

Keep in mind that the end-effector of the haptic device must be held at all times during a trial. The duration of the trial is indicated by the red light, which turns green when the trial is finished (after 30s has passed). At the end of a trial you can let go of the end-effector and let the haptic device return to its home position. Afterwards the countdown starts again and you need to hold on to the end-effector.

Types of feedback:

- Visual feedback will be provided by the tv-screen showing the pendulum states
- Haptic feedback will be provided in the form of shared control, where guidance forces help you balance the pendulum

In short

Your task:

- Keep angle as small as possible
- Judge which feedback is delayed

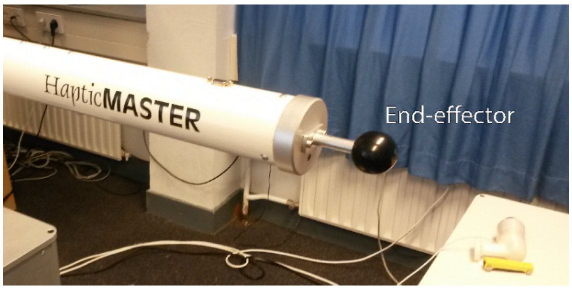

Figure 15. End-effector of the HapticMaster.

- Hold on to end-effector during a trial

Procedure:

1. Training (±10min)
   - Familiarize with set-up, try to balance the pendulum
   - Try to balance the pendulum with visual delays
   - Try to balance the pendulum with haptic delays
2. Experiment (± 80-110min)
   - 5 training, then judge delay
   - 5 recorded trials, keep angle as small as possible

If you have any questions, feel free to ask before the experiment. Specific questions may be answered after the experiment if it may influence the experiment. When you need a break during the experiment you can let me know. If you feel informed sufficiently please read and sign the informed consent form.