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Dynamic Guiard: Haptic Feedback of Disturbance Effects and Relative Dynamic Motion in Robotics

Master Thesis

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Abstract

Teleoperation enables performing tasks that are too demanding, too dangerous or spatially difficult to reach for direct human operation. Depending on the application, teleoperated robots operate in environments that are subject to dynamic disturbances, such as the movement of organs in teleoperative surgery. In single robot arm operations, one hand, usually the non-dominant hand, is not used. By perceiving the disturbance as dynamic feedback, incorporating this non-dominant hand into the teleoperation loop might help to compensate for the disturbance. In this thesis, we therefore explore Guiard's theory of bimanual control for dynamic disturbance to the non-dominant hand. In the course of the manuscript, we refer to this concept as *Dynamic Guiard*. A VR study with 24 participants was conducted where they had to perform hold and tracking tasks in a moving environment exposed to a variety of disturbances. The motion of the environment was displayed to the non-dominant hand as force feedback, position feeback and without feedback as control condition. The study results show great potential for *Dynamic Guiard* in improving the performance of teleoperation in disturbed environments. The analysis indicates, for instance, that force feedback to the non-dominant hand can help as an indicator of direction and velocity of the environment motion. A potential application could be to provide sudden gusts of wind on an aerial manipulator as a force reference directly to the non-dominant hand of the teleoperator to increase accuracy during the operation.

Zusammenfassung

Teleoperation ermöglicht die Durchführung von Aufgaben, die für den direkten Einsatz von Menschen zu anspruchsvoll, zu gefährlich oder räumlich schwer zu erreichen sind. Je nach Anwendung arbeiten teleoperierte Roboter in Umgebungen, die dynamischen Störungen ausgesetzt sind, wie z.B. Bewegungen von Organen in der teleoperativen Chirurgie. Bei Operationen mit einem Roboterarm wird in der Regel die nicht-dominante Hand nicht benutzt. Die Einbeziehung dieser Hand in die Teleoperation kann helfen, die Störung zu kompensieren, indem die Störung als dynamisches Feedback an die nicht-dominante Hand übertragen wird. In dieser Arbeit untersuchen wir daher Guiards Theorie der bimanuellen Interaktion für dynamische Störungen an der nicht-dominanten Hand. In Rahmen dieser Arbeit haben wir diesen Ansatz *Dynamic Guiard* genannt. Hierbei wurde eine VR-Studie mit 24 Teilnehmenden durchgeführt, bei der die Teilnehmenden Positionshalte- und Trackingaufgaben in einer sich bewegenden Umgebung durchführen mussten, welche einer Vielzahl von Störungen ausgesetzt war. Die Bewegung der Umgebung wurde der nicht-dominanten Hand in Form von Kraft Feedback, Positions Feedback und ohne Feedback angezeigt, letztere als Kontrollbedingung. Die Ergebnisse der Studie zeigen, dass die Einbindung von *Dynamic Guiard* großes Potenzial für die Verbesserung der Performance der Teleoperationen in gestörten Umgebungen hat. Unter anderem kann Kraft Feedback an die nicht-dominante Hand als Indikator für die Richtung und Geschwindigkeit der Umgebungsbewegung dienen. Eine mögliche Anwendung könnte darin bestehen, plötzliche Windböen auf einen Aerial Manipulator als Kraft Feedback direkt an die nicht-dominante Hand des Teleoperators weiterzugeben, um ihre/seine Genauigkeit während der Operation zu erhöhen.

Contents

Introduction

"Humans will work with robots to gain new knowledge" according to ESA's current vision. Teleoperation is expected to play an important role in this, as it gives us the ability to extend human cognition to space and various spatial areas on earth. Telerobotic systems that involve a human operator who operates the robot remotely [16], thus, combines the human's perceptual and problem-solving capabilities with the robot's technical capabilities. Teleoperation is especially used for tasks that are too dangerous or demanding for direct human operation, or that need to be performed in an environment that is inaccessible to humans [21]. The areas of application range from surgical to underwater operations. Depending on the specific application, a robotic system must operate in an environment that is subject to dynamic disturbances, such as wind or dynamic coupling between the end effector and the object. Dynamic coupling effects are often referred to as internal disturbances, while those already mentioned are called external disturbances [1, 5]. Telerobotic systems that experience disturbances include aerial, underwater and space manipulators. They need to deal with disturbances caused by wind [10], water current[3] or discrete thruster effects [12], as shown in Figure 1.1. Surgical telerobotics face the challenge that during surgery, natural movements of organs, such as those caused by the heartbeat, require compensation movement [8]. One system for example that struggles with disturbances is the cable-Suspended Aerial Manipulator (SAM), on the left in Figure 1.1. SAM is an unmanned aerial vehicle (UAV) of the German Aerospace Center (DLR) with a robotic arm mounted on the underside which is controlled via teleoperation [14]. Since UAVs are naturally exposed to wind disturbances, performing tasks with SAM's robot arm poses a challenge to the robot and its human teleoperator.

Solutions are required to make teleoperation robust against disturbances. Quite popular is the use of automatic control algorithms for disturbance compensation, e.g., through approaches using sliding mode or disturbance observers [12]. However, these control algorithms suffer from limitations, for instance, inaccuracies still persist, especially in the presence of highly dynamic and unpredictable disturbances. Thus, performing tasks without a stable position currently remains a major challenge. For this reason, it is necessary to investigate new approaches.

The present work explores the human's haptic capabilities to compensate for errors caused by disturbances. This new approach is not to technically optimize the robotic

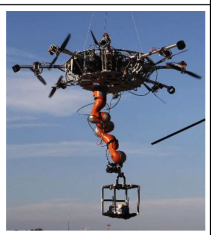
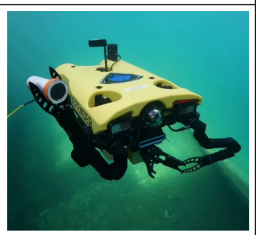
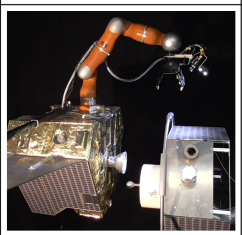
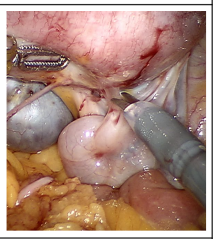
Domain	Aerial	Underwater	Space	Surgery
Image				
Disturbance Effects	Wind, dynamic coupling	Water currents, dynamic coupling	Discrete thruster effects, dynamic coupling	Organ motion, dynamic coupling

Figure 1.1 Overview of teleoperative domains that experience disturbances.

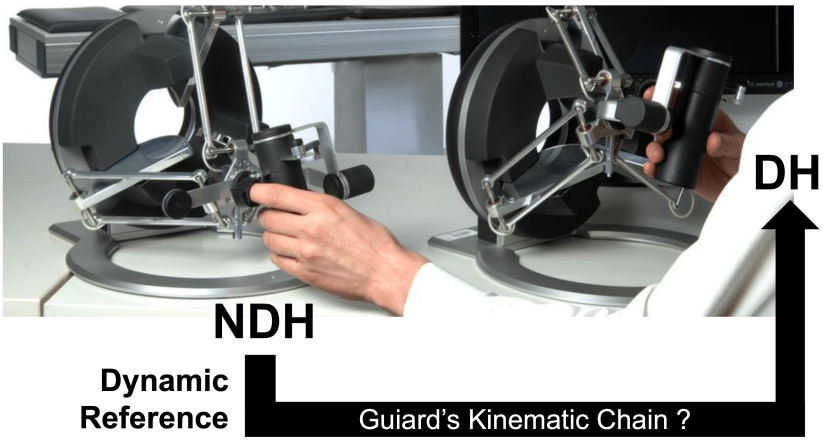


Figure 1.2 Illustration of the research purpose of investigating the Guiard's kinematic chain in the teleoperation context with dynamic reference to the NDH.

system, but to improve the human-machine interface (HMI) between the human operator and the controlled robot by allowing the operator to perceive the disturbance haptically. Hereby, we assume that humans can complement the compensatory motion of the robot to increase performance since humans can interpret and forecast the dynamic disturbance better than a robot. HMIs in teleoperation mainly use the combination of haptic hand devices and videostream of the teleoperated environment (on a computer screen or via HMD) [16]. Considering the functionality and role of both hands in teleoperation, the present work makes a crucial distinction between the dominant hand (DH) and the non-dominant hand (NDH). A unimanual operation which uses a single robot arm, as in the case of SAM, is usually performed by the DH of the human operator. During this **single arm operation**, the operator's NDH is not or hardly used at all.

Since humans are generally skilled to perform tasks with two hands, for which **Guiard** [4] developed a model, this non-involvement of the NDH creates a possibly missed opportunity for interaction. According to Guiard's theory the DH and NDH always work in reference to each other. This may present a potential for improving the interaction in a teleoperated system. However, there are only studies based on Guiard using the NDH as static reference. In this work this is referred to as *Static Guiard*. Ullrich et al. [18] found that incorporating the NDH as a static reference for the operating DH already improves operation in a virtual environment, proving Guiard's theory for static referencing. No studies have been found that have investigated the involvement of the NDH as a dynamic reference. Similar to *Static Guiard*, the NDH might be incorporated as a reference into the unimanual operation so that dynamic disturbances on the robotic system are perceived in the NDH and the caused errors are compensated directly through the kinematic loop to the DH. Due to the lack of in-depth research in this area, the present work addresses the **research question:** *Does dynamic referencing to the non-dominant hand help in a task with the dominant hand?*

Among others, this thesis extends for the first time the Guiard Theory to dynamic references to enhance the teleoperation performance in complex perturbative robotic applications. The research question is illustrated in Figure 1.2. In order to determine whether dynamic feedback on NDH has a fundamental impact on the operating DH, an exploratory user study with 24 participants was conducted as part of this thesis to search for effects of dynamic referencing in the teleoperation context. To highlight the difference from Ullrich's work, we

Figure 1.3 Study setup of our user study conducted within the framework of the thesis.

have called this new research approach *Dynamic Guiard*. In the experiment, participants had to perform different tasks on a moving platform with the DH while receiving the corresponding dynamic reference on the NDH via a haptic device (compare left hand in Figure 1.3). The task performance corresponded to the measured accuracy. For the dynamic reference, the position and force reference were examined against each other and in comparison to the control case without reference. An improved accuracy with force reference was found at higher accelerations. It remains open to what extent the findings can be explained by the Guiard Theory.

Related Work

Related work was found in the areas of control algorithms for disturbance rejection, telehaptics, and the psychophysical research of bimanual interaction.

2.1 Control algorithms for disturbance rejection

The general approach to deal with disturbances is to use automatic disturbance compensation algorithms in the robotic system to eliminate the perturbations directly at the robot. The two most popular methods are the use of sliding mode and adaptive controllers [12]. In sliding mode control (SMC), the state of the robot system is brought to a predefined sliding surface that results in the desired compensated zero state. The system moves along the glide surface, making it robust to disturbances. For underwater manipulators, performance with SMC is adequate for smaller perturbations, but not for larger perturbations, such as shallow depths and large wave heights [19]. However, SMC suffers from drawbacks such as excessive control overhead and state oscillations around desired values, also known as shattering [12]. The latter can be mitigated by higher order SMC. SMC is also used in surgical telerobotics. For example, in combination with a disturbance observer (DOB) [5]. A DOB is a controller with output feedback whose task is to estimate and discard external disturbances [15]. This mitigates the chattering problem caused by the SMC and improves tracking performance. The opposite approach to feedback control is feed-forward control, developed for example for underwater telerobotics [19]. Here, prediction methods are used that rely on physical models of the disturbances. These may be hydrodynamic or aerodynamic models, for example. For underwater manipulators, an average improvement of 17% can be achieved with rough estimates. Control algorithms are in general intensively studied in literature, leading to new insights and improvements. However, there are still inaccuracies, especially in the presence of disturbance variables that are difficult to estimate and change rapidly over time. Disturbance compensation by the teleoperator proposed in the present work can provide faster results, especially using force reference to the non-dominant hand (NDH), since the measured acceleration from the disturbance can be transferred immediately without going through a complex control system.

2.2 Telehaptics

The incorporation of haptic feedback from external inputs into teleoperation is referred to as telehaptics. Humans complete the control loop by sending haptic command signals to and

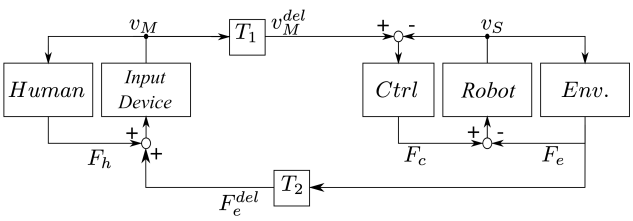


Figure 2.1 Signal flow diagram of a bilateral teleoperator with measured force feedback. A human operator uses a haptic input device (Input Device M) to control a robotic manipulator (Robot S) in its environment, considering time delays T [11].

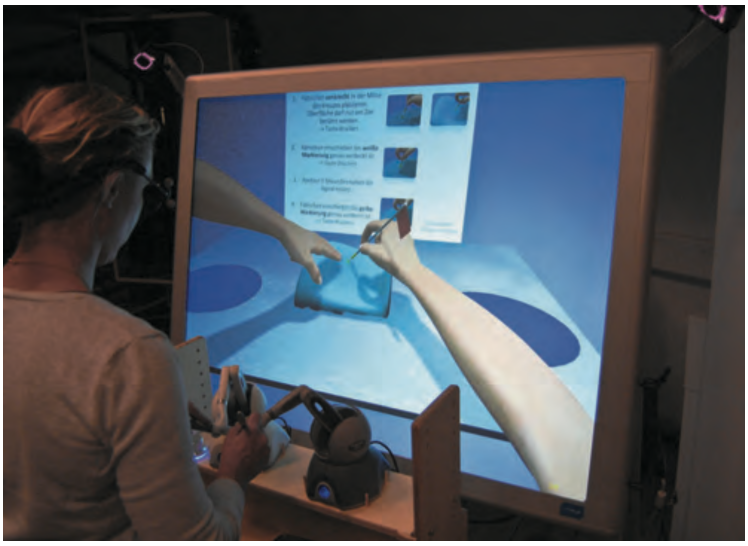


Figure 2.2 Ullrich's study setup for bimanual operation in a virtual environment, using the NDH as a static reference for the operating DH. The test subject is in a standing pose wearing tracked stereo glasses. The virtual hands are controlled with two haptic devices [18].

receiving haptic feedback from the remote teleoperated robot, as illustrated in Figure 2.1. The key research question is currently how to design the system to best support human decision making and action while ensuring robust operation of the system [6]. Haptic feedback is used in various areas of teleoperation, for example for space manipulators [9] or in teleoperative surgery. However, haptics has been absent from commercial telesurgery robots until recently, although research and development on haptics for teleoperative systems has been ongoing for more than two decades [13]. The focus of current research in telehaptics is mainly on the study of direct haptic feedback between the manipulated robot and the manipulating input device. The term robot refers to the robotic system being moved. The input device refers to the system being operated by a human teleoperator. Haptic teleoperation can be unimanual or bimanual. In unimanual operation, the robot is operated with one hand; in bimanual operation, the robot is operated with both hands. In both cases, the hands maneuver the input device while receiving haptic feedback from the moving robot. There are some improvement approaches such as the model-based haptic telemanipulation (MATM) approach, where the haptic feedback to the human is a combination of real and augmented virtual feedback [7]. To the best of the author's knowledge, there is no literature in which both hands are divided into one manipulating and one non-manipulating hand in bimanual teleoperation, or in which one hand passively receives haptic feedback from the moving robot in a unimanual operation, as will be investigated in this thesis.

2.3 Psychophysical research of bimanual interaction

More relevant literature was studied extensively from the psychophysical perspective of bimanual interaction. According Talvas et al. [17], experiments using both hands to perform grasping tasks indicate that learning processes are transmitted between both hands as well as haptic information, with trajectory information being transmitted from the NDH to the dominant hand (DH) and endpoint position information being transmitted from the DH to the NDH. Brain imaging studies also indicate the presence of neural networks that control

the coordination of both hands during bimanual activities. Of particular note is the Guiard Theory [4]. The Guiard Theory states that there is a bimanual frame of reference. Both the NDH and the DH serve as references to each other and form a kinematic chain. However, the relationships between sensations in both hands and motor control of these hands are largely unexplored. Ullrich et al. [18] investigated Guiard's theory in a virtual environment. The experiment was conducted with 13 participants under two different conditions: bimanual and unimanual. As can be seen in Figure 2.2, the interaction task was based on a surgical setting and consisted of a sequence of pointing, aligning, and docking subtasks for the DH. The NDH served as a static reference for the DH based on Guiard. Both hands are visually represented in the virtual enviromnent to increase embodiment. This is accompanied by the "rubber hand illusion," an embodiment phenomenon in which the simultaneous stroking of a rubber hand in view with one's own hidden hand is sufficient to produce a false sense of ownership [2]. The results of Ullrich et al. showed that mean values for accuracy were mostly better in the bimanual case. Also, the task completion times were significantly shorter in the bimanual case. According to the survey of Talvas et al. [17] bimanual interaction in general helps to combine different subtasks into a single, less cognitively demanding task, and that the degree of asymmetry used to accomplish a task correlates directly with the difficulty of that task. Further Talvas et al. states that the entire state of knowledge about bimanual interaction must be taken into account when developing bimanual haptic hardware, software, and interaction techniques, otherwise the benefits of this form of interaction may be lost. This is where the Guiard Theory and the present study comes in, by considering the relationship between DH and NDH in teleoperation.

Theory & Concept

This chapter is about the theory and building concept behind the study. The theoretical basis is provided by the Guiard Theory which motivates the research on Dynamic Guiard. The concept of the study is based mainly on how the dynamics on the non-dominant hand (NDH) should be displayed to the user, i.e. in which modality, in which temporal sequence and whether the hand should be displayed visually.

3.1 Guiard Theory

The Guiard Theory describes a kinematic chain model between human's limbs, where they form a chain of reference in series, as shown in Figure 3.1 following three major principles [17]: 1. the NDH is a frame of reference for the dominant hand (DH), 2. the NDH precedes the DH in its actions and 3. both hands act at different temporal and spatial scales, with the NDH acting at a rougher scale. The Guiard model is mainly applied to two-handed interactions where the NDH and the DH act like motors. The motors are controlled by an information processing system (IPS) that functions analogously to the human brain when the motor represents a human hand. A reference position (RP) generates an input to the motor, and the output of the motor generates a variable position (VP). The reference position (RP) for the NDH is the input for the NDH motor. After the movement of the NDH motor, the NDH generates a variable position (VP), which together with the RP for the DH becomes the input for the DH motor. The movement of the DH then generates a VP for the DH. This chain can contain many motors in a serial order, and the VP for the DH can then become part of the input to the next NDH motor. According to Guiard's model, the chain should always start with the NDH and normally end at the DH [20].

Guiard can be applied, for example, to sports, where both NDH and DH perform different tasks. In archery, the NDH provides stability and coarse aiming, while the DH provides accurate aiming. Guiard can also be applied to drawing. The NDH on the sheet of paper, not only holds the sheet, but also serves as a static reference position for the DH drawing on the paper, which is called *Static Guiard* in this thesis.

3.2 Dynamic Guiard

The Guiard Theory, in particular its first principle, implies that a reference changing in time, i.e. a dynamic reference, could also be represented by Guiard's kinematic chain. If this is the case and dynamic referencing between NDH and DH behaves similarly to *Static Guiard*, a first draft of the kinematic chain model based on Guiard's theory is illustrated in Figure 3.2. In order to determine whether dynamic feedback on NDH has an impact on the operating DH as it can be interpreted from the Guiard Theory, a VR user study in the teleoperation context was conducted as part of this thesis.

3.3 Dynamic modalities

Since dynamic referencing between NDH and DH has not yet been deeply investigated, it has been challenging to find out how to provide dynamic feedback to the NDH. In general, motion can be subdivided into the three different kinematic quantities: position, velocity and acceleration. However, these kinematic quantities can be represented individually as different

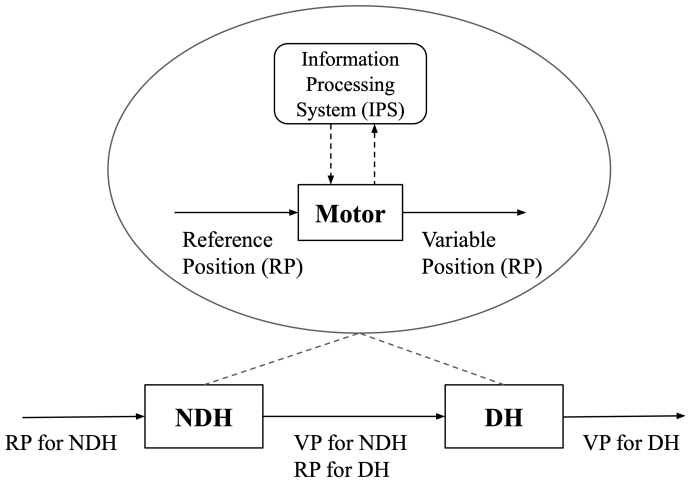


Figure 3.1 Guiard's kinematic chain model [20] for bimanual interaction between NDH and DH.

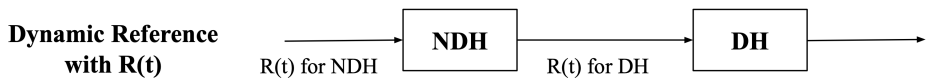


Figure 3.2 Possible kinematic chain model for dynamic reference R(t) investigated in this thesis.

haptic modalities to the NDH, i.e. mapping, as shown in Figure 3.3. They do not have to correspond to the same physical modality. For example, the position or velocity of an object can be haptically represented as a force, but also as an position. Or vice versa the position can be rendered haptically as a force. Motion can be therefore represented haptically in different forms. This means that an intersectionality of the different dynamic output forms is possible and therefore has an effect in regards of dynamic referencing. Since human haptic perception sensors are based on force or position, the position can be haptically displayed by transferring it directly to an moving object held with the NDH. On the other hand, the acceleration can be displayed as a force pressing on the NDH. In this case, however, the force giver (haptic device) and the force taker (arm) must be spatially fixed together such that there is no movement that would interfere with the movement of the hand that is displayed as force.

Basically, there are three kinematic quantities to choose from, each of which can be represented by two different haptic modalities to which Guiard's theory can be applied - but only if this theory also applies to dynamic referencing, which is the main investigation of the thesis. Since human haptic perception focuses primarily on haptic changes in position and the influence of force, it was to first look at the modalities: position and force. With regard to robotics, the robot can measure force accurately. The position, needed for compensation by control algorithms, is obtained by double integration which produces possible inaccuracies. Thus, providing the human with force information, the human can probably compensate for the error better than the robot. An intersectional combination between modality and kinematic quantity was not investigated for now. Therefore, the modalities correspond to the kinematic quantities with the position haptically represented as a position and the acceleration multiplied by a mass as a force. Here, as shown in Figure 3.3, the dynamic reference conditions were the position and acceleration of the platform compared to the

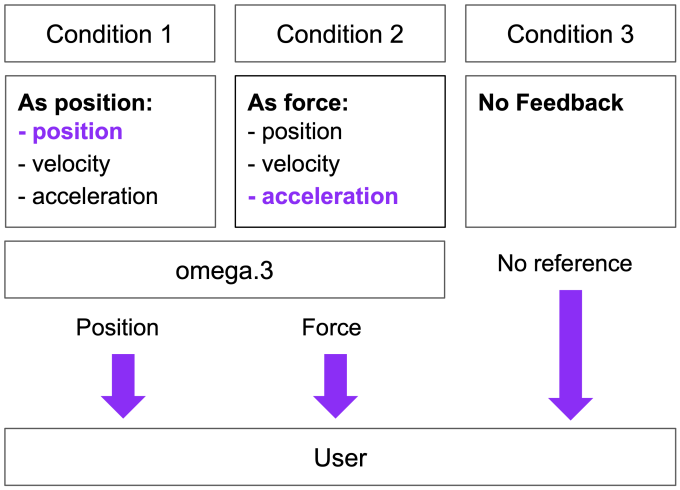


Figure 3.3 Overview of possible dynamic modalities and those used for the study highlighted in purple.

case without dynamic referencing. Thus, it was expected to find similar effects as in static referencing where Guiard Theory has already been confirmed. Note, that the control condition without dynamic referencing is not considered as static referencing here, since the platform is in motion, i.e. it is not static, just the motion is no longer haptically rendered to the NDH.

3.4 Motion profiles

After clarifying which dynamic modality to study, we designed motion profiles that reference the NDH via the modality. The challenge in finding motion profiles includes two aspects that were important to consider here. First, it is important for the applicability to make the profiles as realistic as possible. Second, since there is no in-depth research in this field yet, it is necessary to have generic and comparable profiles in order to make general valid statements.

The first approach was to create profiles according to the cause principle (disturbance = known, resulting motion = unknown). This means that the profiles were not created directly, but focused on the disturbance forces and the resulting motion. Based on the plot of the resulting motion, possible generic profiles were searched. Unfortunately, no recorded measurements of the SAM system under wind disturbance at DLR were found. Also, in literature no other recordings of aerial, underwater, or space manipulators under disturbances were available. Therefore, a 6-DoF mass model with spring-damping coupling between simulated manipulator and aerial platform was used as a substitute. Generic force profiles as simulated disturbances were then applied to this model. Due to the high number of degrees of freedom, the 6-DoF model made it difficult to handle the creation of profiles. In addition, it was not clear which modalities to use at this point, so reducing the degrees of freedom was the next reasonable step to minimize confounding variables. In a second approach, a 2-DoF model was used, which made it easier to create comparable profiles. Since the 2-DoF model simplifies real-world behavior considerably, the question arose of whether to create the profiles directly, which was less time-consuming and offered more control in the design.

After careful consideration, the second approach was chosen, namely to create the motion profiles directly according to the "you get what you see" principle (disturbance =

unknown, resulting motion = known). Although, the creation of realistic profiles produced by disturbances is more difficult to create this way, the greater design control allows more general and selective investigations. The generated profiles represent the motion as only one kinematic quantity, either acceleration, velocity or position. Since we are focusing here on the force and position modality, we need to get the acceleration and position from the profile. If the profile represents acceleration, it must be integrated twice. If it represents velocity the profile must be derived once and integrated once, or it must be derived twice if the profile represents position. The process of deriving and integrating place different requirements on the profile design. When integrating a profile as an acceleration profile or a velocity profile, it is difficult to create complex position profiles, because they in turn require more complex derivation designs that can only be found in a time-consuming iterative process. When deriving a profile as a position profile, on the other hand, it must be ensured that the profile is twice continuously differentiable. If not properly addressed, artificial discontinuities or corners in acceleration profiles can cause undesired study disturbances. Finally, we chose to use continuously differentiable position profiles to compare force and position modalities, which required similar levels of complexity for both. Accomplishing this with acceleration profiles as a basis posed a great challenge.

A variety of position profiles have been tested, ranging from proprietary trigonometric functions to complex polynomial functions. In this process, the profiles also had to be designed to match the workspace of the used devices, see Section 4.4. The focus was on three different function types: (quasi-)periodic functions, jump functions and step functions. Pure periodic functions are constructed using trigonometric functions with a fixed frequency. A quasi-periodic function, on the other hand, is a polynomial function that does not follow a fixed period, but with similar frequencies, so it is also haptically perceived as a periodic function. A step function represents a single change in position. The jump function, as its name says, represents a jump between two positions. The jump function was excluded on the assumption that the second half of the positional jump was predictable for participants. A similar phenomenon was also evident when testing the (quasi-)periodic functions. Frequency is a good comparison parameter, but frequency functions also have the problem of becoming predictable after the first amplitude. The periodic predictability of the profile helps the participant. It makes it hard to tell whether the improvement is due to the periodic predictability or the feedback itself. Therefore, periodic predictability represents a confounding variable that should be avoided in studies. For this reason, the step function was chosen, as it provides low predictability on its own.

Another important question to resolve was whether one-dimensional or two-dimensional position profiles should be used. As mentioned above, reducing the degrees of freedom was important in order to minimize as many confounding variables as possible. Two-dimensional profiles in the x-y plane provided a good basis at the start. However due to the task design for the DH, it was necessary to design the profiles only one-dimensionally, here along the y-axis, that no confounding variable arises for the second task (see Section 4.2). The one-dimensional reduction also results in a greater comparability.

Based on the smooth-step function in Eq. 3.2, six different position profiles were created for the study, as shown in Figure 4.2. The smooth-step function used here is an analytically cut-out of a 7th-order polynomial function, Eq. 3.1, which was further developed for the study. As shown in Figure 3.4, the new developed function consists of two slopes on both sides, with an optional linear region defined by how long the duration T for both slopes is set and its gradient a. For the reason of variation, this linear region is used in profiles 4 to 6 and not in profiles 1 to 3. The Profiles are 25 seconds long and contain 6 or 8 position

changes. Emphasis was placed on changing between different positions and for different lengths. Profiles come in varying degrees of difficulty. For this purpose the profiles were divided into two groups. Profiles 1-3 have 6 shifts and profiles 4-6 have 8 shifts. The duration of position change decreases in both groups with increasing acceleration. Acceleration is on average higher for profiles 4-6 than for profiles 1-3. Moreover, the profiles include surprise effects which means that after several back and forth movements, also two successive forward or backward movements occur. The profiles all start at position zero, but end at different positions. The corresponding force profiles, which are also illustrated in Figure 4.2, are obtained by deriving the position profile twice to get the acceleration and then multiplying it by a fictive mass.

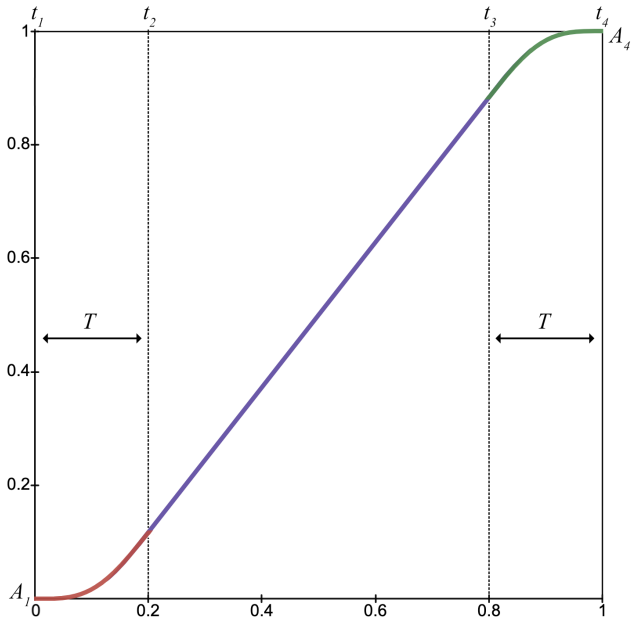


Figure 3.4 Self-developed smooth step function of 7th-order with a linear region in the middle based on Eq. 3.2.

$$g(x) = -20x^7 + 70x^6 - 84x^5 + 35x^4 \qquad \text{(smooth step function of } 7^{\text{th}}\text{-order)} \tag{3.1}$$

$$f(t) = \begin{cases} a\frac{32}{35}\left(t_2 - t_1\right) g(k) + A_1 & \text{for } k = \max\left(0, \min\left(0.5, \frac{t-t_1}{2(t_2-t_1)}\right)\right) \text{ if } t_1 \leq t < t_2 \\ a\left(\left(t - t_2\right) + \frac{16}{35}\left(t_2 - t_1\right)\right) + A_1 & \text{if } t_2 \leq t < t_3 \\ a\frac{32}{35}\left(t_4 - t_3\right) g(s) + \left(A_4 - \frac{32}{35} a\left(t_4 - t_3\right)\right) & \text{for } s = \max\left(0.5, \min\left(1, \frac{(t-(2t_3-t_4))}{2(t_4-t_3)}\right)\right) \text{ if } t_3 \leq t \leq t_4 \end{cases} \tag{3.2}$$

$$a = \frac{(A_4 - A_1)}{(t_3 - t_2) + \frac{16}{35}(t_2 - t_1) + \frac{16}{35}(t_4 - t_3)} \qquad \text{(gradient at } t_2 \leq t < t_3\text{)}$$

$$t_2 = t_1 + T$$

$$t_3 = t_4 - T$$

where the given parameters are:

t_1 = start time
t_4 = end time
A_1 = start amplitude
A_4 = end amplitude
T = slope duration

3.5 Dummy hand

The study also includes a fake virtual NDH positioned for all conditions, as shown in Figure 3.5. The motivation was to create a hand embodiment, based on the "rubber hand illusion" [2], that creates a visual reference of the motion to the NDH. Virtual hands were also included in the study of Ullrich et al. [18] to establish a connection and comparability to this study. However, only the visual representation of the NDH was considered for realistic reasons. A visual representation of the DH in teleoperation would interfere with the view of the operating end effector.

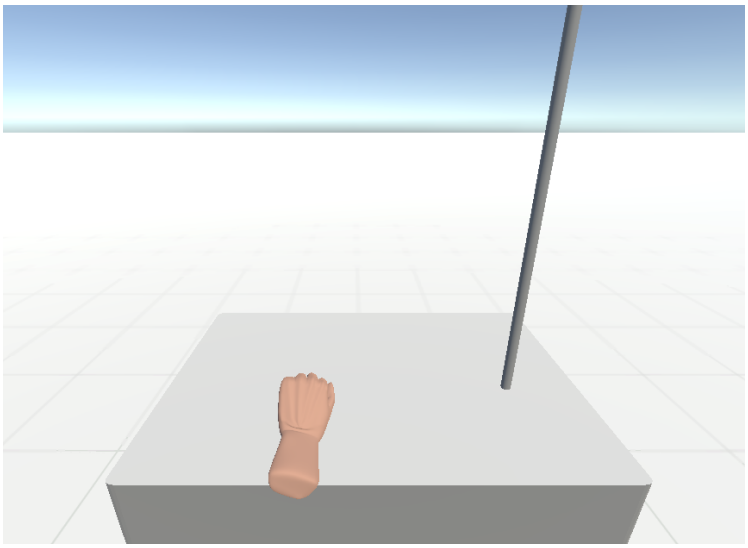


Figure 3.5 Virtual study environment with dummy hand.

Study Design

The present study is an haptic user study in a virtual environment. Each participant had to perform two different tasks (Task 1 and 2) virtually with the dominant hand (DH) on a moving platform, while the motion of the platform was haptically displayed to the non-dominant hand (NDH) as *Position reference* and *Force reference*. For control purposes of the experiment, the tasks were also performed with *No reference*. To complete the task, participants had to compensate for the different movements of the platform (defined by the Motion Profiles 1 to 6) with the DH as accurately as possible. In total there were 36 subtasks, 12 per condition. The individual conditions was evaluated on the error of compensation. Figure 4.1 shows a breakdown of the study.

An exploratory study requires a wider scope of investigation, which in turn means a larger set of conditions and tasks. To enable this with a small number of study participants, the present study followed the within-subjects approach. All study participants went through all conditions and tasks, but in systematically varied order to counteract the learning effect. In our case, the order of task and condition were varied per participant. The dependent variable was the error of compensation between ideal trajectory and the trajectory executed with the DH. Independent variables were the three conditions, the platform motion profiles, and the Tasks 1 and 2. In summary, the conditions acted on the NDH while the DH performed the tasks.

4.1 Conditions (NDH)

This study considers the two haptic modalities: position and force. Both represented the two conditions to be investigated in comparison to the third control condition without dynamic reference. These include the *Position reference* (Condition 1) and *Force reference* (Condition 2), and *No reference* (Condition 3). The movement of the platform was shown in these modalities by 6 profiles of different difficulty, each with a length of 25 seconds, as shown in Figure 4.2.

4.2 Tasks (DH)

The participants had to perform two tasks with the DH, while they get haptic feedback of the position profiles on the NDH. For this, we used two different task types. The first task was a pure hold task and the second task was a combined track and hold task. In the two tasks the DH moved a rod in the x-y plane. This rod is infinite, i.e., it had no beginning and end, to prevent the participant from making compensatory movements in the z-direction that are irrelevant for this study. This ensured to focus only on the relevant compensations

C	Condition 1												Condition 2												Condition 3											
T	Task 1						Task 2						Task 1						Task 2						Task 1						Task 2					
P	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
S	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36

Figure 4.1 Breakdown of the user study into 3 conditions (C), 2 tasks (T), profiles 6 (P), and 36 subtasks (S) per participant.

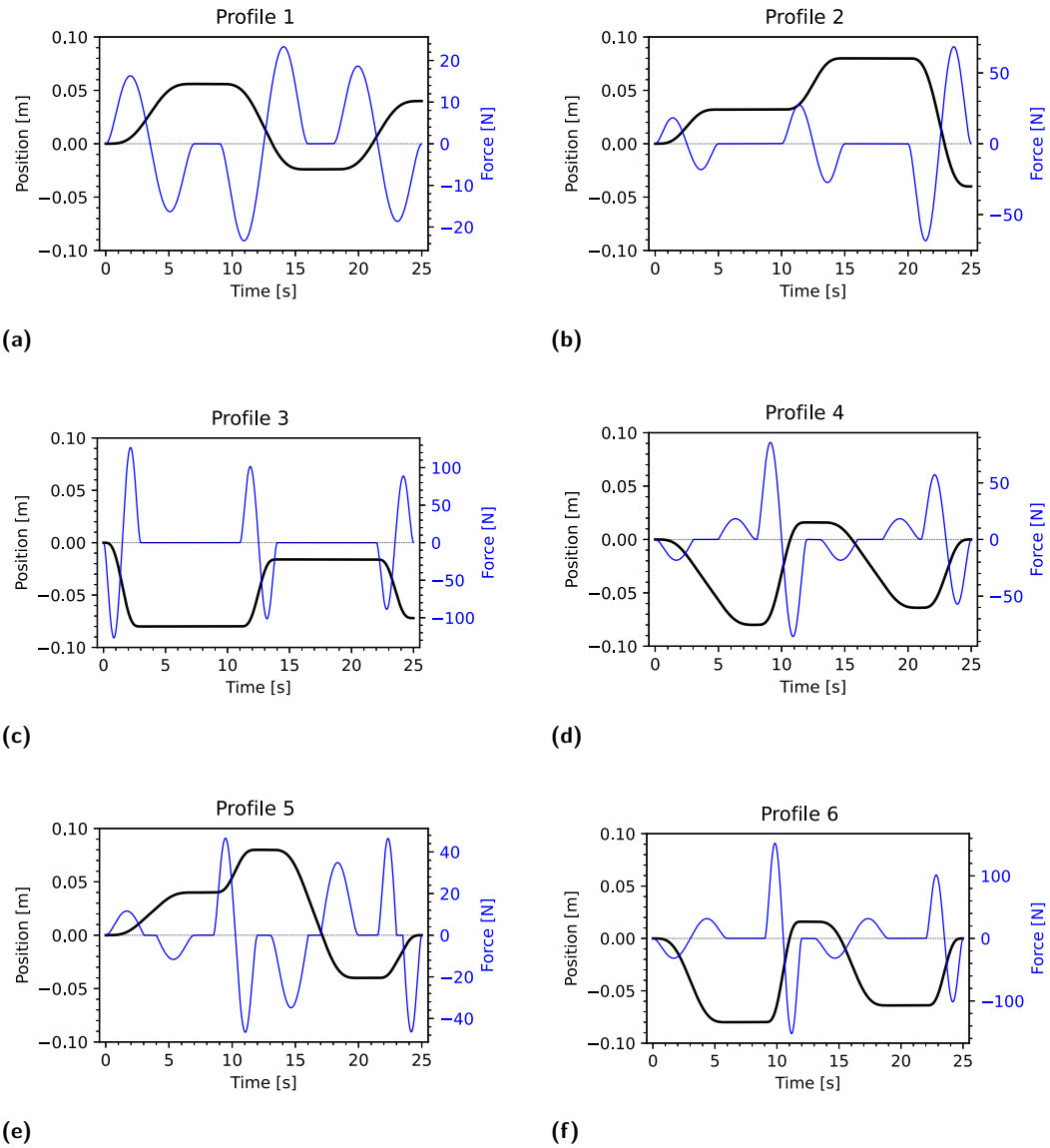


Figure 4.2 Six motion profiles: *Position profiles* (black) generated using Eq. 3.2. The corresponding *Force profiles* (blue) result by deriving the position twice and multiplying it by a fictive mass.

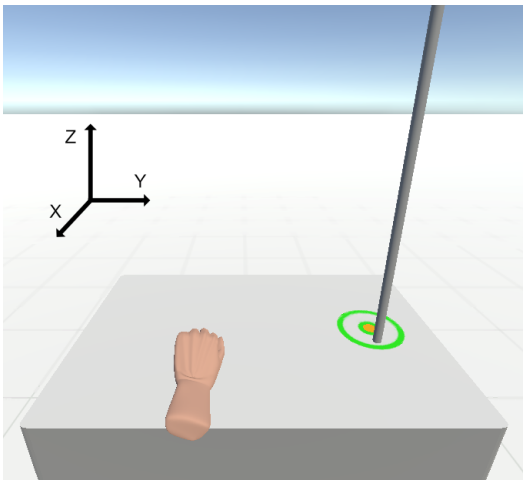


Figure 4.3 Task 1 of the user study.

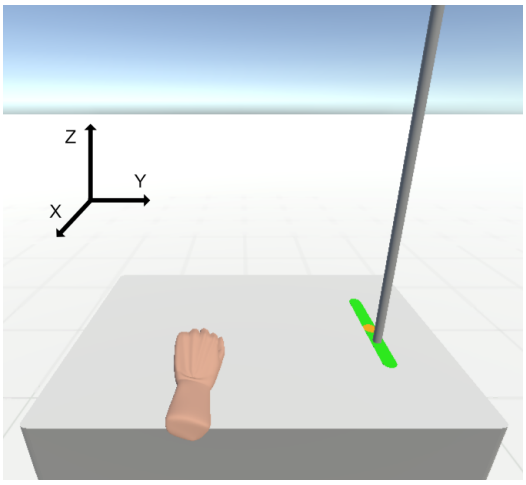


Figure 4.4 Task 2 of the user study.

in the x-y plane.

Task 1 - Hold

In the first task, there was an orange circle inside a target on a virtual platform, as shown in Figure 4.3. The participants had to hold a rod as close to the center of the orange circle as possible while the platform moved in the y-direction according to the designed profiles. Task 1 is therefore a 1-DoF task. As mentioned earlier, this motion was then haptically referenced to the NDH.

Task 2 - Track and Hold

The second task was similar to the first task but slightly more challenging. Again, the rod had to be held in the middle of the orange circle, except that now the orange circle additionally moved along a line in the x-direction, as shown in Figure 4.4, with the length of 12 cm within 25 seconds, resulting in a speed of about 5 mm per second. Therefore, in addition to the movement of the platform, the participants had also to compensate for the orthogonal motion of the orange circle in order to keep the rod in its center. Task 2 is therefore a 2-DoF task in the x-y plane.

4.3 Procedure

The study takes about 1h 20 min per participant. According to the participants' feedback, the length of the study and the task distribution were perceived as not bothersome, but close to it. The procedure is shown in Figure 4.5. For conducting a successful study, the procedure checklists from Appendix E and the subtask checklist from Appendix F were used to avoid human errors. While the procedure checklist was hardly necessary after several trials due to memorization, the subtasks checklist was very important for conducting the study.

Study Introduction

The study started with a brief introduction to the participant:

Stage	**Duration** (approx. 1h 20 min)
Introduction	15 min
Condition 1: - Training - Task 1: - Profile 1-3: - Easy - Medium - Difficult - Profile 4-6: - Easy - Medium - Difficult - Task 2: - See above - Questionnaire	20 min 2 min (30s profile) 4 min 2 min 40 s (25s profile) 40 s (25s profile) 40 s (25s profile) 2 min 40 s (25s profile) 40 s (25s profile) 40 s (25s profile) 4 min 10 min
See above: Condition 2, 3	20 min + 20 min
Post interview	5 min

Figure 4.5 Overview of study procedure with approximate duration of each stage. Note, the order of condition and task varies per participant.

> *This is a VR study with haptic feedback. You will use both machines and we see how well it works. We test the system. If something doesn't go well, it's not your fault. There will be training sessions.*

Then the participants were ask to fill out the informed consent (see Appendix B) and demographic questionnaire (see Appendix C). Afterwards, the individual devices, which are described later in Section 4.4 in detail, and their functions were shortly explained, as followed:

- *The Omega device is only for haptic feedback on your NDH.*
- *The Lambda device is only for control with the DH.*
- *The HMD shows you the image of the virtual environment.*

After filling out the questionnaire, the participants were asked to sit on the stool. Through markings on the floor, the participants were instructed to sit as centrally as possible. They could move the stool forward and backward, depending on their body size and arm length. Essential was that the arrow on the floor was centered between the two legs to ensure a similar distance between lambda and omega, as well as to be in the field of view of the HMD tracking sensors. Next, the armrest with integrated elbow pad and hand fixation was explained for the NDH. The armrest is used in two different ways. For position reference, only the elbow pad is used, and accordingly the armrest is rotated so that the armrest does not interfere with the NDH. The second way of using the armrest is with hand fixation of the NDH, which is used in force reference and no reference. Since the hands of the participants in the study are naturally of different sizes, the hand fixation for the NDH is adjusted in advance. The participant was subsequently introduced to the Lambda input device. The DH

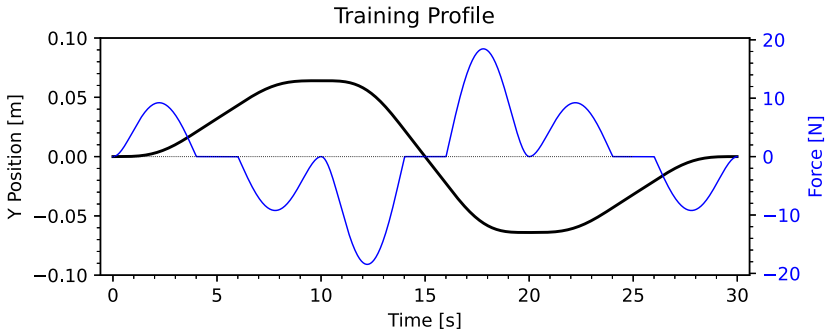


Figure 4.6 Training profile created by using Eq. 3.2 similar to the main profiles.

had to hold the handle while the index finger and thumb had to be inserted into two separate straps. In order to move the input device, i.e. to activate it, the thumb and index finger had to be pinched together. This pinched position had to be hold to move the rod in the experiment. In order to make this process clearer to the participant, this procedure was shown to the participants on the screen of the visualization laptop. For a correct measurement, the participants were asked to pinch their fingers together before starting a subtask. Lastly, the participants were asked to put on the HMD headset. The participants were shown how to adjust the headset to make it as comfortable as possible for them, which included adjusting lens distance for participants who wear glasses, adapting the eye distance and adjusting the headset boom to their head size. Once this was all set, the final step was for the participants to reset the headset to the zero position. This was done through the built-in menu in the HMD, which triggered a 3-second countdown for the reset. During the countdown, the study director positioned the participant's head in the correct viewing direction, for which the study director asked the participant to hold the head loosely. After this initialization of the HMD, the study director brought both hands of the participant to the respective devices. At this point, the study participant was ready to start the study.

Training of tasks and conditions

For each of the three conditions and the two tasks, there was a training session, i.e. a total of five training sessions. For this purpose, a motion profile with a duration of 30 seconds was used, which was particularly developed for the training, as shown in Figure 4.6. The training profile consists of smooth-step functions like the other profiles. After every training session, the study instructor asked the participant whether the participant had fully understood the condition or task. If the answer was yes, the actual experiment continued, if not, the training session was repeated.

Procedure of subtasks and conditions

After each subtask, the participant had to use the DH to reset the bar to the starting point. Additionally, in the force and no reference conditions the participant had to center the ball of Omega with the NDH, too. Measuring could only start when all devices have been centered. After 12 subtasks each condition is completed. The participant was now requested to put down the HMD and fill out the post-condition questionnaire (see Appendix D) corresponding to the completed condition. This was done on a separate desk next to the experimental setup. As soon as the participant finished the questionnaire, he could sit back on his seat and put on

the HMD. Like in the introduction, the participant had to reset the HMD display to the zero position again in the same way as in the introduction. For position reference, it was then explained that the interaction ball of omega should be held as loosely as possible while the NDH is moved. For force reference, it was pointed out that the NDH would now experience forces, while the ball needed be held as fully as possible in the hand fixation. During the explanation, the natural effect of forces was made clear referring to acceleration, which makes an object move, and deceleration, which makes an object stop. With no reference which involved fixing the hand in the same way as with force reference, it was explained that no haptic feedback would be felt on the NDH. The hand was fixed in the same way as with force reference to prevent the participant from subconsciously moving the NDH.

Post Interview

After the last condition, the participant was asked to take part in a final interview. In this conversation general feedback and ideas for improvements were gained with the following open questions:

- *What are your thoughts about the experiment at the moment?*
- *Have you sensed a difference in the various conditions? More precisely, what was helpful? Did something bother you?*
- *How would you rank the conditions?*
- *How did the various feedback impact your interactions?*

4.4 Apparatus

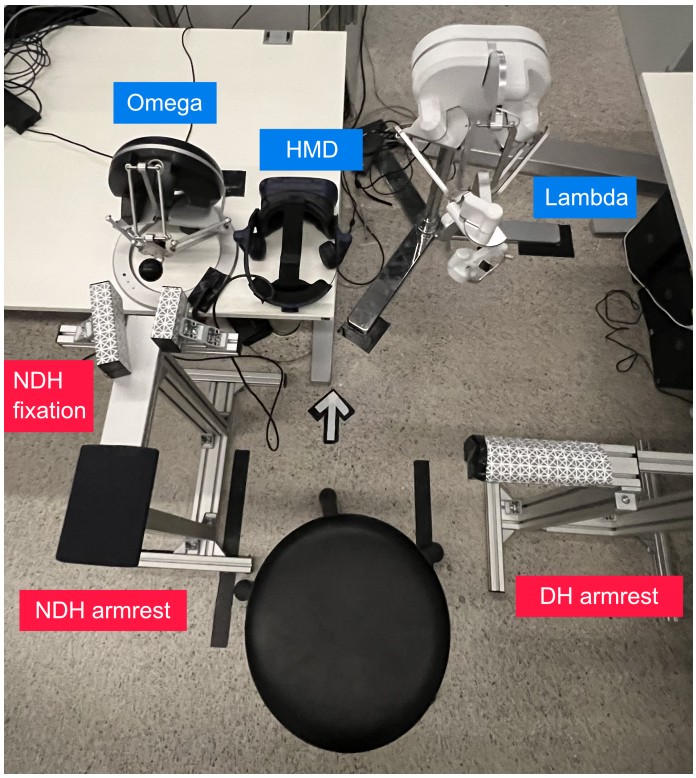


Figure 4.7 Overview of the study setup.

The study setup consists of multiple elements, as shown in Figure 4.7. Three primary devices were used for the study. The omega.3 from Force Dimension, here referred to as Omega, which gives the dynamic feedback to the NDH. Then the lambda.7 also from Force Dimension, referred to as Lambda, for manipulating the rod to perform the tasks with the DH. And finally the HMD display HTC Vive Pro for the VR representation of the experiment environment.

The Omega device has a resolution of < 0.01 mm and and a workspace of ⌀160 x 110 mm. The Lambda device has a translational resolution of < 0.0015 mm and a workspace of ⌀240 x 170 mm. In practice, this means an overlap of the working area of ⌀160 x 110 mm. This is especially important for Position reference as the scaling in the experiment here needs to be the same for both devices. Specified by the manufacturer, Omega provides a force of maximum 12 N, which is relevant for Force reference. The HMD HTC Vive Pro has a resolution of 1440 x 1600 pixels per eye (2880 x 1600 pixels together) with a refresh rate of 90 Hz and field of view of 110 degrees, which is sufficient for the experiment. The VIVE Pro comes with the SteamVR Base Station 2.0, which includes two tracking sensors attached to a railing in the background. The HMD is connected to an extra laptop used only for the visualization. On this laptop the 3D engine Unity in version 2021.3.15f1 is installed, as well as the needed SteamVR software. All devices are connected to the central computer through DLR's Links and Nodes middleware, also known as LN Manager. The main program for the study was programmed using Simulink 2018b and was executed on a Linux computer.

The experiment setup also includes the hand fixation for the NDH which was constructed from aluminium profiles. Furthermore, as described in Chapter 4.1, the NDH must be fixed in order to be able to feel a force with force reference. Since hands vary in size, the hand adjustment is variably adjustable. There is also a soft pad for the elbow in order not to rest directly on the aluminum surface. The elbow also helps for the position reference condition by allowing the elbow to rest while the NDH is moving. In addition, there is another armrest on the right side (DH) with padding for the arm of the actively using DH, to counteract the fatigue effect and tension. This was also constructed with aluminium profiles.

4.5 Measurements

For the objective measurement, the pose of Lambda was measured. The pose describes the position and rotation. In addition, the head tracking of the HMD was also logged. For the main evaluation, only the measured position in y-direction was relevant. The measured position in x-direction is not considered in this study, because the motion takes place only in y-direction and therefore compensation movements are only of interest along this axis. Additionally, the rod visually blocks the view of the participants in order to keep centered in x-direction. To avoid data loss due to computer crashes or other failures, the logged measurement data was saved after each of the 3 subtasks.

Four questionnaires were taken from each participant, the demographic questionnaire (see Appendix C) and three post-condition questionnaires, one for each condition (see Appendix D). The demographic questionnaire includes general information, experiment-related questions about experience with haptic and dynamic systems, and the question whether participants are right- or left-handed. Each post-condition questionnaire is composed of different standardized questionnaires. The included questionnaires are: the Fast Cybersickness questionnaire, the NASA-Task Load Index (NASA-TLX) questionnaire, System Usablity Scale (SUS) questionnaire, the Igroup Presence Questionnaire (IPQ) and the Virtual Embodiment Questionnaire (VEQ). The Fast Cybersickness questionnaire asks the participant's level of

sickness on a scale of 1-20. The NASA-TLX questionnaire helps to evaluate the perceived workload. The SUS questionnaire measures the usability of the system, here, the given HMI concept with Omega, Lambda and the HMD. The IPQ assesses the sense of presence experienced in the virtual environment. Simarily, the VEQ measures the factors of virtual embodiment felt by the participant. Virtual body represents here the position of the camera relative to the moving platform.

After the last post-condition questionnaire, there was the post interview, which was audio recorded with the participant's consent.

Results

The results are divided into the description of the participant demographics, the accuracy based on the measured position errors, the subscales of the post-condition questionnaires and the evaluation of the post-interviews.

5.1 Participants

The study involved 24 participants, all of them employees of DLR. All subjects were right-handed. Attention was paid to take only right-handed participants if possible, given the almost fixed experimental setup. The participants were young. The age of participants ranged from 19 to 49 years with a mean age of 27.2 (SD = 6.6) years. The gender was not balanced by 21 male and 3 female. Most subjects were under-/graduate students (62%) followed by PHD students (12%). Other professions were scientist (13%) and engineers (13%).

With the demographic questionnaire, we also collected information about the experience and knowledge level of the participants. According to the first question, the majority of participants (63%) have no previous experience with force feedback devices, see Figure 5.1. The participants with previous experience (37%) gained it mostly through the work at the Institute of Robotics and Mechatronics of DLR, including surgical robotics (13%). The level of experience with VR has a mean score of 1.0 (SD = 1.1) on a scale of 1 to 5, and is divided into participants having no previous experience 0 (33%), little experience 1 - 2 (54%), and more experience 3 - 4 (12%) with VR. The median hours per week of participants spending in dynamic systems was 5.0 (IQR = 3.5), e.g., driving a car or biking (with side winds), water sports, piloting, robot dynamics. The mean hours per week playing computer games was 2.2 hours with the median of 0 hours (IQR = 2.9). The mean hours per week using 3D design software was 4.2 hours with the median of 0 hours (IQR = 2.8). The majority of subjects (83%) have no problems suffering from sickness within a simulation environment. Most subjects wear glasses or contact lenses (63%). Almost all subjects have no trouble recognizing colors (92%) and perceiving spatial depth (96%).

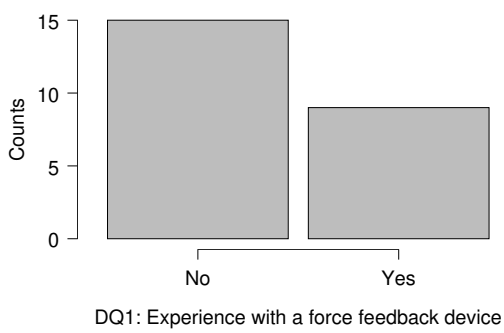


Figure 5.1 Experience of participants with a force feedback device.

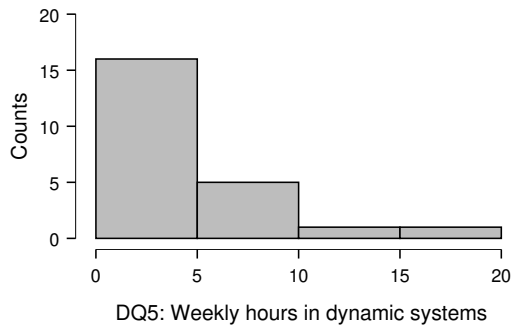


Figure 5.2 Hours per week spent by participants in a dynamic system.

5.2 Accuracy

For evaluation of the accuracy, the root-mean-square deviation (RMSE) between the intended position and the measured position in y-direction was calculated, resulting in the **position error**. From the data only ranges where acceleration occurred were included, so that a comparison between the three conditions: *Position reference*, *Force reference* and *No reference* could be made. Areas where the motion of the environment is nearly linear and the acceleration is close to zero were excluded, since it is also assumed to be irrelevant for the comparison of the three conditions. In total, 42 sections were considered, see in Appendix A, from each of which the RMSE was calculated. The limits of the individual sections were set manually in order to ensure that relevant measured values for instance overshoots were included. For the statistical evaluation, the two-way repeated measurements analysis of variance (rmANOVA) method was applied to the data, as the present study is a within-subject study with repeated measures and multiple within-subject factors. In case of non-sphericity, the Huyn-Feldt correction procedure was used. For the analysis of accuracy depending on condition and task a 3x2x42 (Condition * Task * Section) rmANOVA was applied. For further analysis, the sections were summarized into groups of the same size regarding the maximum acceleration of the environment's motion in each section (see Table A.1 for three groups), also in order to reduce the amount of data. For the analysis of accuracy as a function of acceleration level, a 3x2x2x3 (Condition * Task * Mode * Acceleration) rmANOVA was applied. For the investigation of the accuracy depending on the acceleration direction, here called Mode, a 3x2x2x7 (Condition * Task * Mode * Acceleration) rmANOVA was applied. All main effects from the rmANOVA are summarized in Table 5.1. Subsequent Post-hoc tests (with Holm-Bonferroni alpha level corrections) determine exactly which conditions differ from each other. The average measurement of the position in y-direction and the accuracy per profile are shown in the Appendix A in Figure A.1 - A.12. Note, the sections can be identified here by gray barriers and a corresponding number on top.

Condition

We found a significant improvement of accuracy with *Force reference* compared to *Position reference* ($p<.001$, $d=0.329$ small effect size) and *No reference* ($p<.001$, $d=-0.296$ small effect size). There were no significant differences found between *Position reference* and *No reference*, see Table 5.2 and Figure 5.3.

Condition * Task

Depending on the tasks, for task 1 a significant improvement of the accuracy is found for *Force reference* compared to *Position reference* ($p<.001$, $d=0.442$ small effect size) and *No reference* ($p=.006$, $d=-0.285$ small effect size). There was no significant difference between *Position reference* and *No reference*. For Task 2, the accuracy improves significantly ($p=.003$, $d=-0.307$ small effect size) for *Force reference* compared to *No reference*. The statistical comparison is illustrated in Table 5.3 and in Figure 5.4. In general, participants showed significantly higher accuracy ($p=0.032$, $d=-0.125$ very small effect size) on task 1 than task 2, as shown in 5.4.

Condition * Acceleration

The conditions were also compared for different accelerations, see Table 5.5. For this purpose, the 42 sections were sorted according to their peak acceleration and divided into three ranges

Table 5.1 Main effects on the position error regarding the within factors: Condition, Task, Section, Mode, Acceleration

Cases	df	F	p	η^2
All 42 sections				
Condition	1.565	14.258	<.001***	0.014
Residuals	35.994			
Task	1	5.244	0.032**	0.003
Residuals	23			
Section	41	78.361	<.001***	0.405
Residuals	943			
Condition * Task	1.963	5.814	0.006**	0.002
Residuals	45.158			
Condition * Section	82	4.912	<.001***	0.031
Residuals	1886			
summarized into 3 groups (= 3 ranges of acceleration)				
Condition	1.643	11.600	<.001***	0.026
Residuals	37.799			
Task	1	3.590	0.071	0.004
Residuals	23			
Mode	1	39.206	<.001***	0.034
Residuals	23			
Acceleration	1.891	605.056	<.001***	0.548
Residuals	43.487			
Condition * Task	2.000	5.310	0.008**	0.004
Residuals	47.919			
Condition * Mode	2.000	11.841	<.001***	0.006
Residuals	46.163			
Condition * Acceleration	3.844	20.281	<.001***	0.022
Residuals	88.419			
summarized into 7 groups (= 7 ranges of acceleration)				
Condition	1.646	12.697	<.001***	0.023
Residuals	37.852			
Task	1	4.543	0.044**	0.004
Residuals	23			
Mode	1	33.286	<.001***	0.024
Residuals	23			
Acceleration	3.957	383.817	<.001***	0.485
Residuals	91.000			
Condition * Task	2.000	5.242	0.009**	0.004
Residuals	47.908			
Condition * Mode	2.000	11.103	<.001***	0.005
Residuals	46.741			
Condition * Acceleration	10.000	12.298	<.001***	0.023
Residuals	232.460			

** $p < .01$, *** $p < .001$)

Table 5.2 Comparison of error between *Position reference*, *Force reference*, and *No reference*.

Comparison of conditions	t	p	Cohen's d
Position - Force	4.848	<.001***	0.329
Position - No reference	0.485	0.630	0.033
Force - No reference	-4.363	<.001***	-0.296

*** p < .001

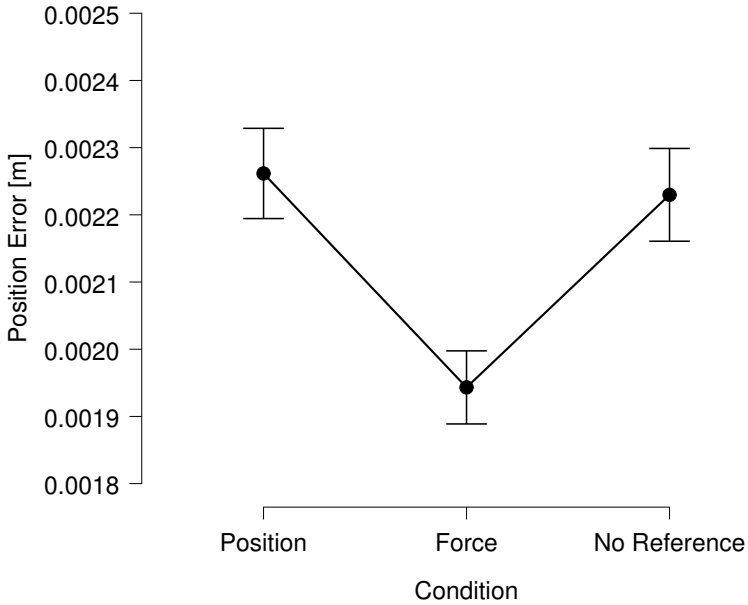


Figure 5.3 Comparison of position error between *Position reference*, *Force reference*, and *No reference* with 95% CI error bars.

Table 5.3 Comparison of position error between *Position reference*, *Force reference* and *No reference* for Task 1 and 2.

Task	Comparison of conditions	t	p	Cohen's d
Task 1	Position - Force	5.601	<.001***	0.442
	Position - No reference	1.992	0.300	0.157
	Force - No reference	−3.610	0.006**	−0.285
Task 2	Position - Force	2.731	0.067	0.215
	Position - No reference	−1.159	1.000	−0.091
	Force - No reference	−3.889	0.003*	−0.307

* p < .05, ** p < .01, *** p < .001

Table 5.4 Comparison of position error dependent on Task 1 and Task 2.

Comparison of task	t	p	Cohen's d
Task 1 - Task 2	−2.290	0.032*	−0.125

* p < .05

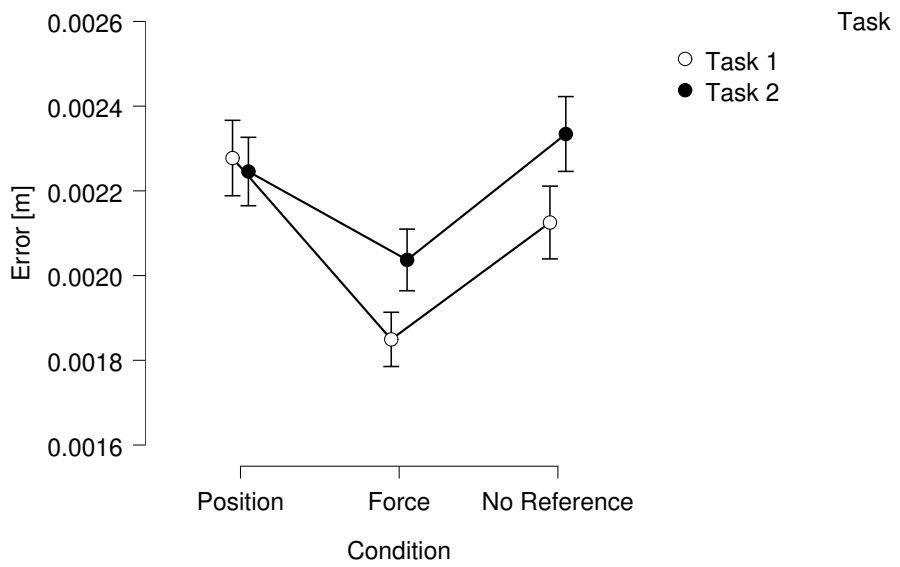


Figure 5.4 Comparison of position error between *Position reference*, *Force reference* and *No reference* for Task 1 and 2 with 95% CI error bars.

with the same amount of sections, as shown in Table A.1 in the Appendix. Next, the RMSE was calculated in these three areas. Accelerations between $6.12 - 14.4 \times 10^{-3} m/s^2$ result in low range, $14.4 - 30.1 \times 10^{-3} m/s^2$ in medium range and $30.1 - 80.1 \times 10^{-3} m/s^2$ in high range. No significant differences were found in the low range. The medium range shows a significant improvement with *Force reference* (p=0.002, d=0.508 medium effect size) over *Position reference* and a possible but insignificant improvement (p=0.067, d=−0.350 small effect size) over *No reference*, otherwise no significant differences were found. In the high range, the *Force reference* is significantly better than *Position reference* (<.001, d=0.955 large effect size) and *No reference* (<.001, d=−1.016 large effect size). No significant differences were found between *Position reference* and *No reference*.

Table 5.5 Comparison of position error between *Position reference*, *Force reference* and *No reference* for low ($14.4 - 30.1 \times 10^{-3} m/s^2$), medium ($14.4 - 30.1 \times 10^{-3} m/s^2$) and high accelerations ($30.1 - 80.1 \times 10^{-3} m/s^2$).

Acceleration	Comparison of conditions	t	p	Cohen's d
Low	Position - Force	0.042	1.000	0.006
	Position - No reference	0.629	1.000	0.085
	Force - No reference	0.588	1.000	0.079
Medium	Position - Force	3.760	0.002**	0.508
	Position - No reference	1.168	1.000	0.158
	Force - No reference	−2.592	0.067	−0.350
High	Position - Force	7.078	<.001***	0.955
	Position - No reference	−0.446	1.000	−0.060
	Force - No reference	−7.525	<.001***	−1.016

* p < .05, ** p < .01, *** p < .001

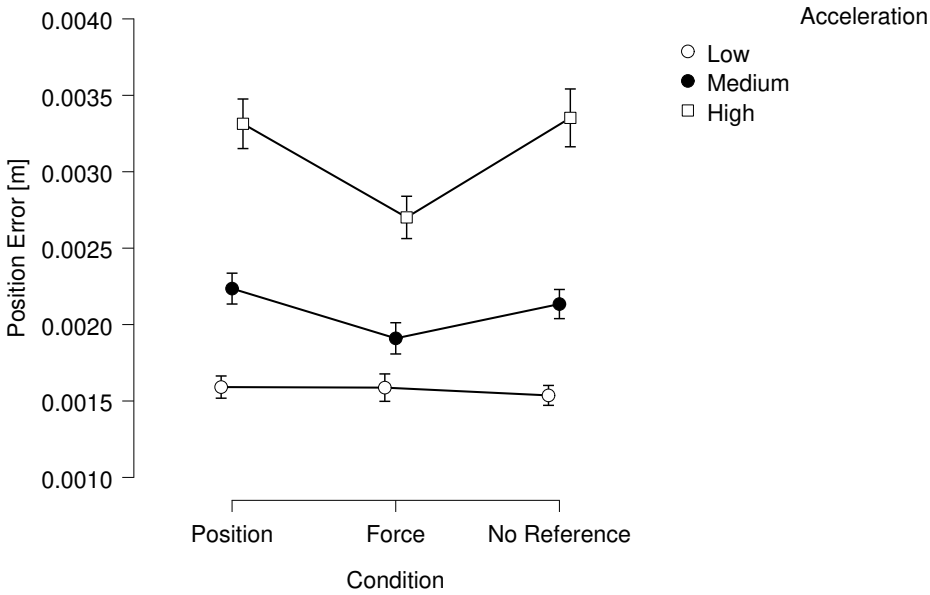


Figure 5.5 Comparison of position error between *Position reference*, *Force reference* and *No reference* for low ($14.4 - 30.1 \times 10^{-3} m/s^2$), medium ($14.4 - 30.1 \times 10^{-3} m/s^2$) and high accelerations ($30.1 - 80.1 \times 10^{-3} m/s^2$) with 95% CI error bars.

Condition * Mode

We also examined the relationship between the condition and the direction of acceleration, i.e. whether it is an acceleration or a deceleration, as shown in Table 5.6. To reduce computational time, the 42 sections were divided into seven ranges with the same amount of sections, sorted by acceleration, for each of which the RMSE was calculated. For the acceleration mode, *Force reference* improves the accuracy significantly over *Position reference* (p<.001, d=0.477 small effect size) and *No reference* (p<.001, d=−0.599 medium effect size), while for the deceleration mode, *Force reference* improves significantly (p=0.002, d=0.421 small effect size) over *Position reference*. Otherwise, no significant differences are observed.

Table 5.6 Comparison of position error between *Position reference*, *Force reference* and *No reference* based on the direction of acceleration: acceleration and deceleration.

Mode	Comparison of conditions	t	p	Cohen's d
Acceleration	Position - Force	4.412	<.001***	0.477
	Position - No reference	−1.122	0.532	−0.121
	Force - No reference	−5.534	<.001***	−0.599
Deceleration	Position - Force	3.888	0.002**	0.421
	Position - No reference	2.268	0.132	0.245
	Force - No reference	−1.620	0.440	−0.175

* p < .05, ** p < .01, *** p < .001

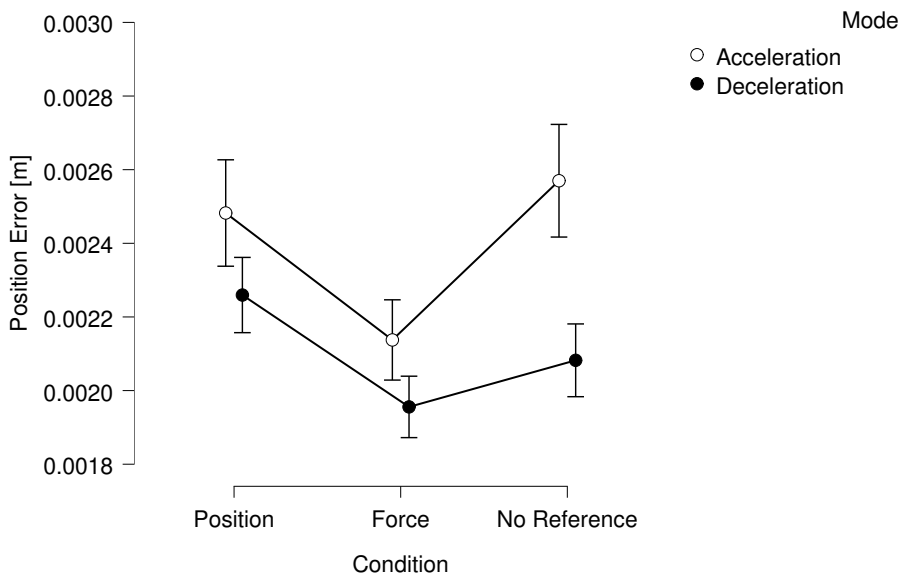


Figure 5.6 Comparison of position error between *Position reference*, *Force reference* and *No reference* based on the direction of acceleration: acceleration and deceleration with 95% CI error bars.

5.3 Questionnaire

For the statistical analysis of the questionnaires, just as in the evaluation of accuracy, the repeated measurements ANOVA method was used, followed by a Post-hoc test (with Holm-Bonferroni alpha level corrections) to determine exactly which conditions differed from each other. The rmANOVA with Condition as within factor was applied for the analysis of each subscale. The data showed no violation of the sphericity assumption.

The evaluated questionnaires were the Fast Cybersickness questionnaire, the NASA-Task Load Index (NASA-TLX) questionnaire, System Usablity Scale (SUS) questionnaire, the Igroup Presence Questionnaire (IPQ) and the Virtual Embodiment Questionnaire (VEQ). No significant differences were observed in the Fast Cybersickness responses. The same applies to the TLX questionnaire with its subscales, as well as the SUS questionnaire, as shown in Table 5.9. Considering Table 5.8, it is observed that the spatial presence (IPQ PR) is significantly better with *Position reference* (p=0.005, d=0.513 medium effect size) and *Force reference* (p=0.003, d=0.557 medium effect size) than with *No reference*. Additionally, force reference improves significantly (p=0.041, d=0.041 small effect size) the involvement which is related to the attention devoted to the VE. Otherwise, no significant differences were found in the IPQ. For the VEQ, a significant improvement of the sense of agency is observed with position (p=0.050, d= 0.315 small effect size) and force reference (p=0.050, d= 0.301 small effect size) compared to no reference. No other significant differences can be seen in the evaluation of VEQ.

5.4 Post Interview

For the post interview analysis, the audio recordings were listened to one by one and summarized in form of statements per participant. Afterwards all statements were grouped together and the frequency of each statement was determined. The most frequent statements

Table 5.7 Main effects on questionnaires' subscales regarding the within factor: Condition

Subscale	Cases	df	F	p	η^2
Cybersickness	Condition	2	1.134	0.331	0.051
	Residuals	42			
NASA-TLX raw	Condition	2	0.170	0.844	0.007
	Residuals	46			
NASA-TLX MD	Condition	2	0.663	0.520	0.028
	Residuals	46			
NASA-TLX PD	Condition	2	0.593	0.557	0.025
	Residuals	46			
NASA-TLX TD	Condition	2	1.043	0.361	0.043
	Residuals	46			
NASA-TLX PF	Condition	2	2.764	0.074	0.107
	Residuals	46			
NASA-TLX EF	Condition	2	0.459	0.635	0.020
	Residuals	46			
NASA-TLX FR	Condition	2	2.252	0.117	0.089
	Residuals	46			
SUS	Condition	2	0.599	0.554	0.027
	Residuals	44			
IPQ G	Condition	2	3.456	0.040*	0.131
	Residuals	46			
IPQ SP	Condition	2	7.607	0.001**	0.249
	Residuals	46			
IPQ INV	Condition	2	3.537	0.037*	0.133
	Residuals	46			
IPQ REAL	Condition	2	0.879	0.422	0.038
	Residuals	44			
VEQ AC	Condition	2	3.938	0.026*	0.146
	Residuals	46			
VEQ CO	Condition	2	2.640	0.082	0.103
	Residuals	46			
VEQ CH	Condition	2	1.864	0.167	0.075
	Residuals	46			

* $p < .05$, ** $p < .01$)

Subscales	Comparison of conditions	t	p	Cohen's d
Cybersickness	Position - Force	0.285	0.777	0.042
	Position - No reference	−1.139	0.523	−0.168
	Force - No reference	−1.423	0.486	−0.210
SUS	Position - Force	1.086	0.850	0.167
	Position - No reference	0.422	1.000	0.065
	Force - No reference	−0.664	1.000	−0.102
IPQ G	Position - Force	−0.409	0.685	−0.081
	Position - No reference	2.045	0.093	0.403
	Force - No reference	2.453	0.054	0.484
IPQ SP	Position - Force	−0.282	0.779	−0.045
	Position - No reference	3.228	0.005**	0.513
	Force - No reference	3.510	0.003**	0.557
IPQ INV	Position - Force	−0.669	0.507	−0.098
	Position - No reference	1.895	0.129	0.279
	Force - No reference	2.564	0.041*	0.377
IPQ REAL	Position - Force	0.059	0.953	0.010
	Position - No reference	1.177	0.737	0.207
	Force - No reference	1.118	0.737	0.197
VEQ AC	Position - Force	0.106	0.916	0.013
	Position - No reference	2.481	0.050*	0.315
	Force - No reference	2.376	0.050*	0.301
VEQ CO	Position - Force	0.592	0.557	0.068
	Position - No reference	2.219	0.094	0.253
	Force - No reference	1.627	0.221	0.186
VEQ CH	Position - Force	−0.612	0.544	−0.096
	Position - No reference	1.280	0.414	0.201
	Force - No reference	1.892	0.195	0.296

Table 5.8 Comparison of questionnaires between *Position reference*, *Force reference* and *No reference* based on the questionnaires Cybersickness, SUS as well as the subscales of IPQ: General presence (G), Spatial Presence (SP), Involvement (INV), Experienced Realism (REAL), and VEQ: Acceptance (AC), Control (CO), Change (CH). * p <= .05, ** p < .01

Subscales	Comparison of conditions	t	p	Cohen's d
TLX raw	Position - Force	0.224	1.000	0.034
	Position - No reference	−0.354	1.000	−0.055
	Force - No reference	−0.578	1.000	−0.089
TLX MD	Position - Force	1.054	0.893	0.184
	Position - No reference	0.930	0.893	0.162
	Force - No reference	−0.124	0.902	−0.022
TLX PD	Position - Force	0.318	0.923	0.068
	Position- No reference	1.061	0.883	0.225
	Force - No reference	0.743	0.923	0.158
TLX TD	Position - Force	−1.160	0.575	−0.168
	Position - No reference	0.166	0.869	0.024
	Force - No reference	1.325	0.575	0.192
TLX PF	Position - Force	0.795	0.430	0.145
	Position - No reference	−1.518	0.272	−0.277
	Force - No reference	−2.314	0.076	−0.422
TLX EF	Position - Force	−0.956	1.000	−0.166
	Position - No reference	−0.538	1.000	−0.093
	Force - No reference	0.418	1.000	0.072
TLX FR	Position - Force	0.477	0.635	0.085
	Position - No reference	−1.552	0.255	−0.275
	Force - No reference	−2.029	0.145	−0.360

Table 5.9 Comparison of questionnaires between *Position reference*, *Force reference* and *No reference* based on the NASA-TLX questionnaire with the overall total score (raw TLX) as well as its subscales: Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Performance (PF), Effort (EF), Frustration (FR).

were: "Force Reference helped me anticipate which direction to go" with 14 mentions. Followed by "Haptic feedback was in general helpful" and "Position Reference helps the most" with nine mentions. Then "Mismatch of dummy hand and real hand" and "Force Reference felt artificial, abstract and unintuitive" with seven mentions each. Other statements were, "Force Reference helps the most" with six mentions, "My dominant arm felt tense at some point" with five mentions, and "Force Reference helped me anticipate how fast the movement will be" together with "With Position Reference I overshoot and have to adjust" with four mentions each. All other statements with their frequency are shown in Table 5.10

Table 5.10 Individual statements from the post-interview, sorted by their frequency.

Statements	Counts
Force Reference helped me anticipate which direction to go	14
Haptic feedback was in general helpful	9
Position Reference helps the most	9
Mismatch of dummy hand and real hand	7
Force Reference felt artificial, abstract and unintuitive	7
Force Reference helps the most	6
My dominant arm felt tense at some point	5
Force Reference helped me anticipate how fast the movement will be	4
With Position Reference I overshoot and have to adjust	4
Haptic feedback was in general not helpful / I felt no difference	3
Visual artifacts (e.g. jumps) were visible	3
Better embodiment with Position Reference	3
My neck was tense from looking down at some point	3
Combine Force Reference and Position Reference	3
At low acceleration Position Reference is better, at high acceleration Force Reference is better	3
Position Reference was parallel to the movement and easy to understand	3
Force Reference: took a little longer to understand it	3
The force gradient was too high, Force Reference behaved like a rectangular function	3
The virtual environment was too abstract	3
Force mapping on velocity would be better	3
Force Reference with acceleration more helpful than with deceleration	2
Low resolution of HMD bothered me	2
HMD felt heavy	2
No Reference made me feel sick	2
Sitting position was not ergonomic	2
Task 1 was easier than Task 2	2
Control of Lambda was accurate and good	2
I had to go too far to the right with DH	1
Position Reference was stressful	1
Better embodiment with Force Reference	1
Hand fixation was annoying	1
Confused that the same device gives deceleration and acceleration feedback	1
Elbow pad was distracting with Position Reference	1
With Force Reference the acceleration came way too early	1
Implement visual fixtures to DH	1
Spatial references in the VE could help	1
I felt motion in the NDH with No Reference	1
I made zig-zag movements with the DH	1
Do a study with eyes closed	1
With No Reference I felt sitting higher	1
Incorporate EMG into haptic studies	1
Implement dummy hand for DH	1

Discussion

The discussion is based on the results of the accuracy, the perceived workload, the usability of the interaction concept, the subjective perceived presence and embodiment, the felt cybersickness and the interviews at the end of the study.

Accuracy

The analysis of the measured accuracy shows no improvement with ***Position reference*** over ***No reference***. This means that transferring the motion directly to the non-dominant hand (NDH) did not produce any effects. Our assumption that a moving reference can achieve similar improvement effects as with static reference, found by Ullrich et al. [18] is therefore rejected for now. Advantages of position reference are more evident in acceleration than in deceleration phases but not significant. Although we expected that Guiard might be less effective in dynamic case, the effects are surprising. The difference regarding acceleration and deceleration indicate that position controller on the Omega device might need to be stronger to achieve higher positioning accuracy. On the other hand, the differences of task 2 with higher spatial complexity compared to task 1 with lower spatial complexity promise that *Dynamic Guiard* with position referencing will support the user more with increasing DoF. The current study presented simple 2-DoF tasks with perfect straight view on the scene which put a comparably low workload on the user.

On the other hand, an improvement of the accuracy with the help of the ***Force reference*** compared to ***No reference*** was found. The improvement turns out to be independent of the complexity of the task. However, it is dependent on the level of acceleration. The higher the acceleration, the higher the improvement showing practical significance at high levels. It should be noted that the found differences between the acceleration levels indicate that we have chosen a suitable range of accelerations for comparison. In general, we argue that force reference behaves as an haptic indicator for the user before the motion is visually noticed, thus improving the user's anticipation. The force reference tells the user whether motion will take place and in which direction. We assume that the reason for this is that acceleration, as the second derivative of position, is much more sensitive to small changes and shows them more prominently and earlier. This interpretation is supported by the fact that force reference only improves performance at high acceleration. At these high accelerations it can be assumed that only the peaks of the force progression are perceived haptically and not the progression itself. This means that the user would only experience the amplitude and direction of a motion with force reference in a discrete manner. The analysis also shows that the improvement with force reference depends on the direction of the acceleration. Only for positive acceleration, the improvement is significantly greater, not for negative acceleration, i.e. deceleration. The reason could be that during the acceleration the NDH is more sensitive with regards to changes. This can be due to changed proprioception in static/dynamic motion and might depend largely on the concentration and relaxation of the non-dominant arm. Also, deceleration is to be expected due to workspace limitations. It remains to be investigated whether the improvement with force reference is also true for several short successive motion sequences, which have not been studied in the present work.

It is worth to mention that with ***No reference***, it becomes more difficult for the user the higher the spatial complexity increases compared to with *Dynamic Guiard* referencing. This shows that possibly higher differences can be found in more complex tasks with more DoFs, which represents an interesting starting point for future investigations. It can also be

seen that no reference becomes more helpful with deceleration.

Workload & Usability

The workload is the same for all conditions. No difference was found. We see the reason for this in the few measurements. Several queries of the workload within the condition would have been interesting, instead of one afterwards. However, there are first signs that the performance with the ***Force reference*** and ***Position reference*** is perceived to be lower compared to ***No reference***, whereas the performance with the no reference is perceived as better. This would be contrary to the objective measurement of accuracy. The reason for this could be that users may perceive force and position reference as disturbances that seem to worsen their performance. The reason could be an increased awareness of the operator's own delayed reaction. We see potential for further investigation to see to what extent this might be a perception paradox. For the usability of the interactions concept, we also found no difference between the conditions. We argue that this is because each condition only makes a small difference with respect to the usability of the overall system, i.e., the usability was dependent on other more important factors, like the usability of the Lambda device which was the same for all conditions.

Presence & Embodiment

The analysis shows that ***Force reference*** and ***Position reference*** allow for a higher spatial presence than ***No reference***. This is an important result since it matches the relative improvement by the position reference with regards to the second task which is spatially more complex. Although we expected the force reference to be counterintuitive, we argue that the dynamic reference for the NDH related to movements in the virtual environment (VE) provide the user with a better understanding of the dynamics in the VE allowing her/him to be more physically present and involved in the VE. This effect kicks in as soon as the task becomes more demanding in more DoFs. The analysis also shows that force reference has a improved understanding of dynamics than no reference. However, the results indicate a low practical significance. We see the need for more measurements here.

For the ***Position reference*** and ***Force reference*** a higher sense of control in the VE compared to ***No reference*** was found. This finding is interesting because the position reference is passively transmitted to the user, i.e., there is no additional active control through the operator. It is possible that this is an expression of the perceived kinematic chain of Guiard. Just the involvement of both hands, whether passive or active, is apparently sufficient to give the user the feeling of more control. This also opens up a potential for further investigation to what extent the embodiment of systems in the VE can be increased by considering the Guiard Theory. For instance, Guiard could be used as a measurement tool to study the embodiment of certain robot hands in a static scenario. However, the resulting effect size indicates limited practical application. Similar to the case of presence, we see a need for more measurements of embodiment based on multiple factors, including different levels of acceleration.

Cybersickness

The analysis showed no difference in cybersickness. We argue that this is due to the fact that the user sits motionless in the VE and sees only simple movements in front of him that are maximally two-dimensional. In our opinion, in all conditions the discrepancy between movements in the virtual and real world is not sufficiently low.

Interviews

The results from the interviews show that ***Position reference*** and ***Force reference*** are perceived as helpful and ***No reference*** not. This is in line with the results for presence and embodiment, but not with the analysis of accuracy. It is interesting that spatial presence and the sense of agency are the only found important factors why haptic reference is in general perceived as more helpful in the interviews. We therefore argue that the perception of haptic feedback as helpful tends to be related to embodiment and presence rather than perceived workload, including performance. However, as mentioned above, the reason for this could also be the lower statistical power, as there are not enough points of measurement.

For ***Force reference***, the statements are consistent with the analysis of accuracy. The most frequent statement was that force reference helped to anticipate which direction to go, which as we argued before can explain the improved accuracy. Less frequently, it was said that it helped to estimate how fast the motion resulting from the disturbance will be. This statement together with statements about the force gradient being too high and behaving like a rectangular function is interesting, however, we see also effects at mid-range accelerations where it is not just discrete. Still, the necessity of dynamic realism has to be further investigated in future work. Nevertheless, these statements support our interpretation of the force reference acting as an indicator for direction. The statements about the acceleration being more helpful in positive direction than in negative direction fits with the results from the objective data. Interesting is that force feedback is seen as helpful, but at the same time as artificial, abstract and unintuitive. Furthermore, participants said that it took a while to understand force reference. We argue that both statements can be related to the lack of experience of most participants. And also that it is counterintuitive to see the hand in motion but only feel forces. Perhaps the hand needs to be positioned and visualized differently for the force reference, or not at all.

For ***Position reference***, it was mentioned that overshoot occurs which requires the user to readjust. This statement is consistent with the measurement of accuracy. We argue that the overshooting probably has to do with the poor performance in deceleration. It was also pointed out in the interview that the position reference is easy to understand because the motions were parallel to the motion in the VE. This makes sense because, unlike the case of no reference and force reference, the visual and haptic representation of the movements matches. The statement that position reference enables a better embodiment supports the result of the embodiment questionnaire showing an improved sense of agency.

The interviews also show that some users did not find their sitting position ergonomic and experienced initial fatigue effects, for example, the neck became stiff when looking down or the dominant arm became tense despite the available armrest. We see the possibility of optimization here. A different perspective in which the user looks straight and a different implementation of the armrest could help. In rare cases, visual artifacts (e.g. jumps) were mentioned which we attribute to interferences with the SteamVR Base Station. The HMD was criticized in a few cases, especially its weight and the low resolution which is justifiable from our point of view, since the resolution was sufficient for fulfilling the tasks. However, for further research, a lighter HMD can be probably helpful against neck tension. It was also noted that the VE was too abtract. However, this was necessary to reduce confounding variables. The mismatch of dummy hand and real hand was also frequently noted. We argue that this is because each participant had different body sizes, but the position of the dummy hand was fixed. Since this circumstance was the same for all conditions, no influence on the result is expected.

Also, suggestions and proposals during the interview were made. For example, the

combination of different reference modalities was suggested, e.g. position reference at low accelerations and force reference at high accelerations. However, the main reason not to do it, is that the understanding of the system would probably be critically reduced. It was also suggested to map the velocity as force. This approach was considered during the development of the study design, but since it would have increased the size of the study, it was discarded. Future studies could explore this approach further.

Conclusion

Teleoperation is used to control robotic systems remotely. Depending on the application, these robotic systems operate in environments that are subject to dynamic disturbances, such as wind. Control algorithms for disturbance compensation, which are widely used for this purpose, are limited and do not provide satisfactory results until present time. This problem is tackled here with **Guiard Theory** [4] by investigating the haptic capabilities of the human operator to compensate for errors caused by disturbances. The Guiard Theory states that the **dominant hand (DH)** and **non-dominant hand (NDH)** operate in reference to each other. In a unimanual operation which uses a **single robot arm**, the robot arm is usually controlled by the DH of the human operator. During this single arm operation, the operator's NDH is often not used which shows that there are dual-hand tasks which are still not considered. Based on Guiard, this creates an opportunity to incorporate the NDH for disturbance compensation. Previous studies show that using Guiard with the NDH as static reference increases the performance in teleoperation. The present research aims to find out to what extent you can transfer Guiard from static to dynamic environments. We called this new research approach **Dynamic Guiard**.

A VR user study with 24 participants was conducted as within-subject study. We investigated users' subjective perception and the accuracy of the DH for different tasks without (No reference) and with dynamic reference in a moving virtual environment. There were two tasks to perform while the environment moved along one axis. In the first task, a rod had to be held in the center of a circle. In the second task, the circle was additionally moved along an axis orthogonal to the axis of the moving environment. As dynamic reference, we displayed the motion of the environment to the NDH as position feedback (**Position reference**) and the corresponding acceleration as force feedback (**Force reference**) via an additional haptic device. In general, it can be said that dynamic referencing has an positive influence on the performing DH. We found that *Force reference* to the NDH improves the user's anticipation. The results indicate that it serves primarily as a discrete indicator of which direction and how fast the environment will move for accelerations over $30mm/s^2$. Furthermore, no improvement was found with *Position reference* but results hint that it was more helpful with increasing spatial complexity of the task. Regarding operator's subjective perception, the involvement of both hands is sufficient to give the operator a higher **sense of control** and **spatial presence**, although this does not necessarily translate into increased accuracy.

We see great potential that *Dynamic Guiard* can help improve teleoperation in disturbed environments. Dynamic reference as a force can increase the accuracy for teleoperation with disturbance under certain conditions. For example, the heartbeat, which also influences the movement of organs, could be given as a force reference directly to the NDH of the surgeon during a surgical teleoperative procedure, increasing his accuracy during the procedure. Since in robotic systems the acceleration is directly measured by IMU sensors, force reference can help the operator with low time delays and comparably high accuracy even before a control algorithm starts to reject the disturbance. However, the results are so far limited to single high accelerations. The validity regarding rapid successive accelerations has to be analyzed in future research, together with more continuous irregular force profiles. Future studies should further investigate to what extent the findings regarding force referencing can be explained by the Guiard Theory. It would also be interesting to explore whether mapping velocity as a force can also have an effect. Questions arise about why does operators' perception

and the actual improvement diverge? How to deal with the deceleration phase? Is it due to proprioception or workload, or does the user rely too much on the support, given by the force and position reference? This study has opened new exciting possibilities for further investigation.

References

References

1 Yanjie Chen, Weiwei Zhan, Bingwei He, Lixiong Lin, Zhiqiang Miao, Xiaofang Yuan, and Yaonan Wang. Robust control for unmanned aerial manipulator under disturbances. *IEEE Access*, 8:129869–129877, 2020. doi:10.1109/ACCESS.2020.3008971.

2 H. Henrik Ehrsson, Nicholas Paul Holmes, Richard E. Passingham, and John H. R. Maunsell. Touching a rubber hand: Feeling of body ownership is associated with activity in multisensory brain areas. *The Journal of Neuroscience*, 25:10564 – 10573, 2005. URL: https://api.semanticscholar.org/CorpusID:18637842.

3 Daniel C. Fernández and Geoffrey A. Hollinger. Model predictive control for underwater robots in ocean waves. *IEEE Robotics and Automation Letters*, 2(1):88–95, 2017. doi:10.1109/LRA.2016.2531792.

4 Yves Guiard. Asymmetric division of labor in human skilled bimanual action. *Journal of Motor Behavior*, 19(4):486–517, 1987. PMID: 15136274. arXiv:https://doi.org/10.1080/00222895.1987.10735426, doi:10.1080/00222895.1987.10735426.

5 Shuang Hao, Lingyan Hu, and Peter X. Liu. Sliding mode control for a surgical teleoperation system via a disturbance observer. *IEEE Access*, 7:43383–43393, 2019. doi:10.1109/ACCESS.2019.2901899.

6 Sandra Hirche and Martin Buss. Human-oriented control for haptic teleoperation. *Proceedings of the IEEE*, 100(3):623–647, 2012. doi:10.1109/JPROC.2011.2175150.

7 Thomas Hulin, Michael Panzirsch, Harsimran Singh, Andre Coelho, Ribin Balachandran, Aaron Pereira, Bernhard M. Weber, Nicolai Bechtel, Cornelia Riecke, Bernhard Brunner, Neal Y. Lii, Julian Klodmann, Anja Hellings, Katharina Hagmann, Gabriel Quere, Adrian S. Bauer, Marek Sierotowicz, Roberto Lampariello, Jörn Vogel, Alexander Dietrich, Daniel Leidner, Christian Ott, Gerd Hirzinger, and Alin Albu-Schäffer. Model-augmented haptic telemanipulation: Concept, retrospective overview, and current use cases. *Frontiers in Robotics and AI*, 8, 2021. URL: https://www.frontiersin.org/articles/10.3389/frobt.2021.611251, doi:10.3389/frobt.2021.611251.

8 M. Joinié-Maurin, B. Bayle, L. Barbé, and J. Gangloff. Force feedback teleoperation with physiological motion compensation. *IFAC Proceedings Volumes*, 42(16):425–430, 2009. 9th IFAC Symposium on Robot Control. URL: https://www.sciencedirect.com/science/article/pii/S147466701530673X, doi:https://doi.org/10.3182/20090909-4-JP-2010.00073.

9 Guanyang LIU, Xuda GENG, Lingzhi LIU, and Yan WANG. Haptic based teleoperation with master-slave motion mapping and haptic rendering for space exploration. *Chinese Journal of Aeronautics*, 32(3):723–736, 2019. URL: https://www.sciencedirect.com/science/article/pii/S1000936118302577, doi:https://doi.org/10.1016/j.cja.2018.07.009.

10 N. Mimmo, A. Macchelli, R. Naldi, and L. Marconi. Robust motion control of aerial manipulators. *Annual Reviews in Control*, 49:230–238, 2020. URL: https://www.sciencedirect.com/science/article/pii/S1367578820300171, doi:https://doi.org/10.1016/j.arcontrol.2020.04.006.

11 Michael Panzirsch, Harsimran Singh, Thomas Krüger, Christian Ott, and Alin Albu-Schäffer. Safe interactions and kinesthetic feedback in high performance earth-to-moon teleoperation. In *2020 IEEE Aerospace Conference*, pages 1–10, 2020. doi:10.1109/AERO47225.2020.9172665.

12 Evangelos Papadopoulos, Farhad Aghili, Ou Ma, and Roberto Lampariello. Robotic manipulation and capture in space: A survey. *Frontiers in Robotics and AI*, 8, 2021. URL:

https://www.frontiersin.org/articles/10.3389/frobt.2021.686723, doi:10.3389/frobt.2021.686723.

13 Rajni V. Patel, S. Farokh Atashzar, and Mahdi Tavakoli. Haptic feedback and force-based teleoperation in surgical robotics. *Proceedings of the IEEE*, 110(7):1012–1027, 2022. doi:10.1109/JPROC.2022.3180052.

14 Yuri S. Sarkisov, Min Jun Kim, Davide Bicego, Dzmitry Tsetserukou, Christian Ott, Antonio Franchi, and Konstantin Kondak. Development of sam: cable-suspended aerial manipulator. In *2019 International Conference on Robotics and Automation (ICRA)*, pages 5323–5329, 2019. doi:10.1109/ICRA.2019.8793592.

15 Hyungbo Shim. Disturbance observers. In *Encyclopedia of Systems and Control*, pages 1–8. Springer London, 2020. URL: https://doi.org/10.1007%2F978-1-4471-5102-9_100068-1, doi:10.1007/978-1-4471-5102-9_100068-1.

16 Weiyong Si, Ning Wang, and Chenguang Yang. A review on manipulation skill acquisition through teleoperation?based learning from demonstration. *Cognitive Computation and Systems*, 3:1–16, 2021. URL: https://uwe-repository.worktribe.com/output/7318640, doi:10.1049/ccs2.12005.

17 Anthony Talvas, Maud Marchal, and Anatole Lécuyer. A survey on bimanual haptic interaction. *IEEE Transactions on Haptics*, 7(3):285–300, 2014. doi:10.1109/TOH.2014.2314456.

18 Sebastian Ullrich, Thomas Knott, Yuen C. Law, Oliver Grottke, and Torsten Kuhlen. Influence of the bimanual frame of reference with haptics for unimanual interaction tasks in virtual environments. In *2011 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 39–46, 2011. doi:10.1109/3DUI.2011.5759215.

19 Kyle L. Walker, Adam A. Stokes, Aristides E. Kiprakis, and Francesco Giorgio Serchi. Feed-forward disturbance compensation for station keeping in wave-dominated environments. *CoRR*, abs/2304.05222, 2023. arXiv:2304.05222, doi:10.48550/arXiv.2304.05222.

20 Xu Xia, Pourang Irani, and J. Wang. Evaluation of guiard's theory of bimanual control for navigation and selection. In *Interacción*, 2007. URL: https://api.semanticscholar.org/CorpusID:15225989.

21 Chenguang Yang, Jing Luo, and Ning Wang. Chapter one - introduction. In Chenguang Yang, Jing Luo, and Ning Wang, editors, *Human-In-the-loop Learning and Control for Robot Teleoperation*, pages 1–15. Academic Press, 2023. URL: https://www.sciencedirect.com/science/article/pii/B978032395143200005X, doi:https://doi.org/10.1016/B978-0-32-395143-2.00005-X.

Measurements

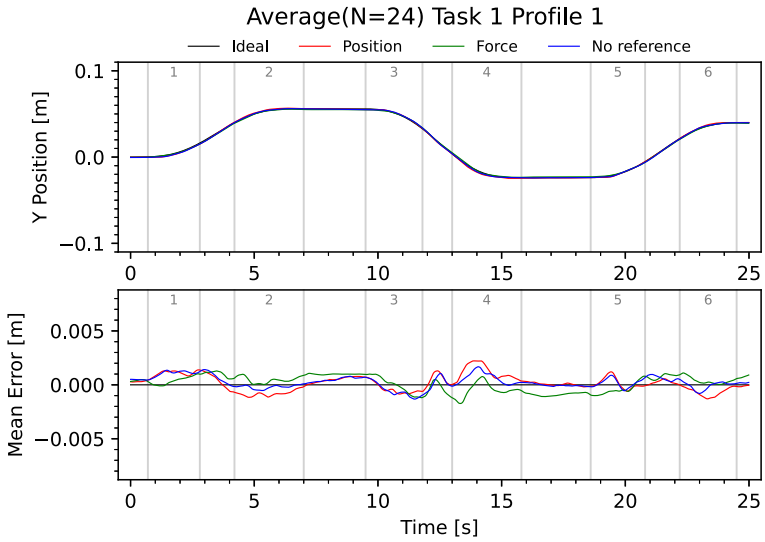
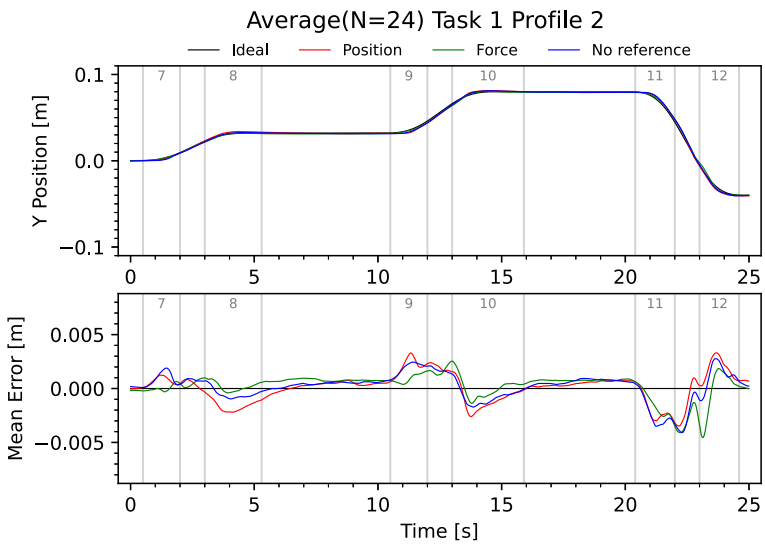


Figure A.1



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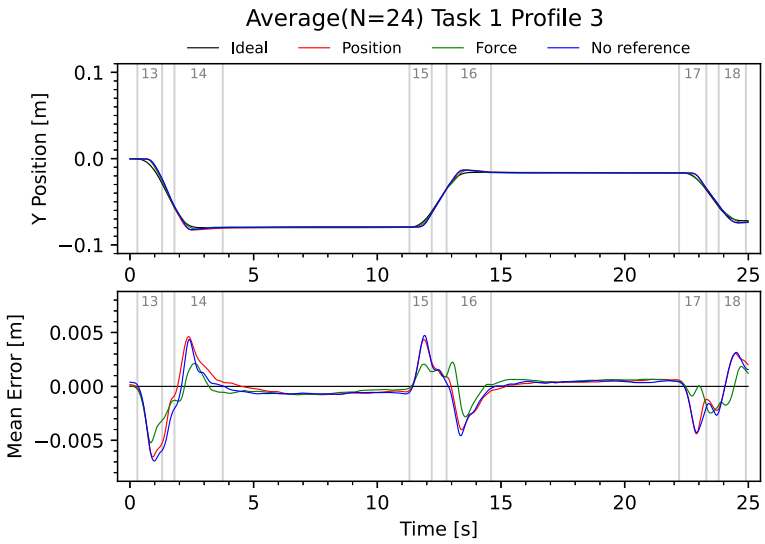

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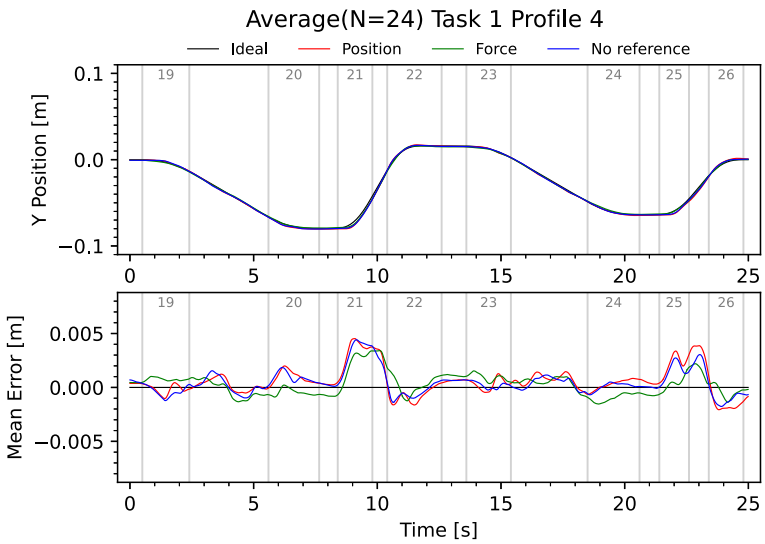

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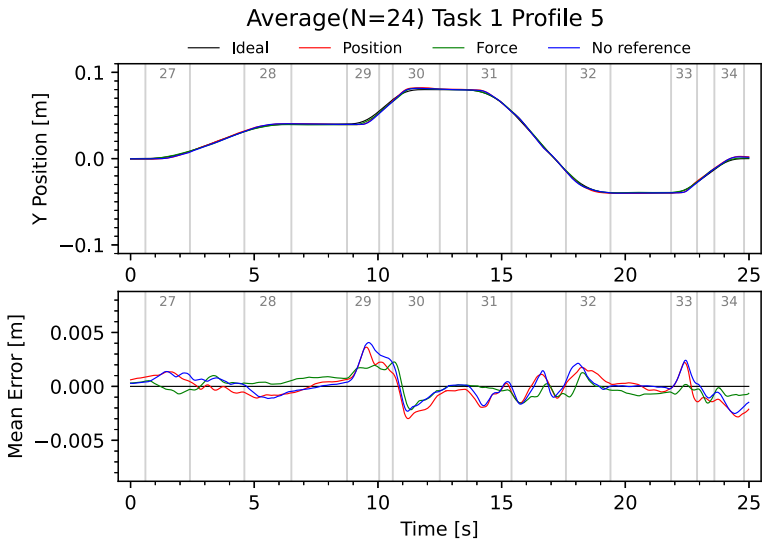

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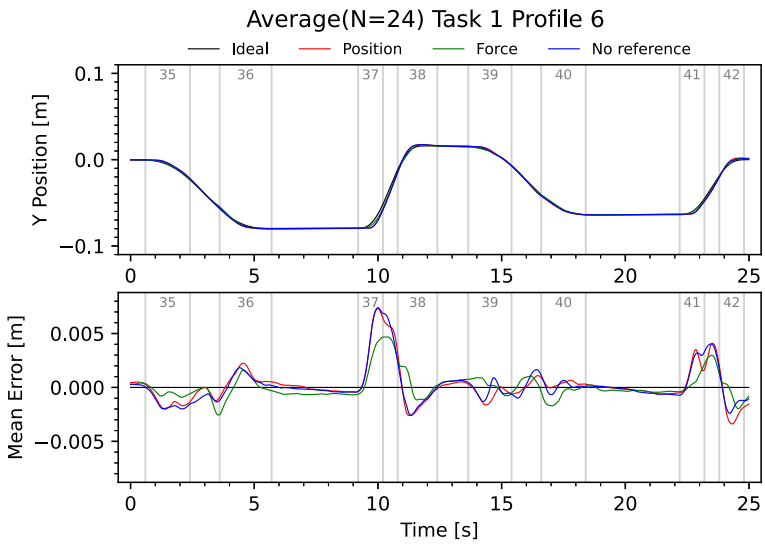

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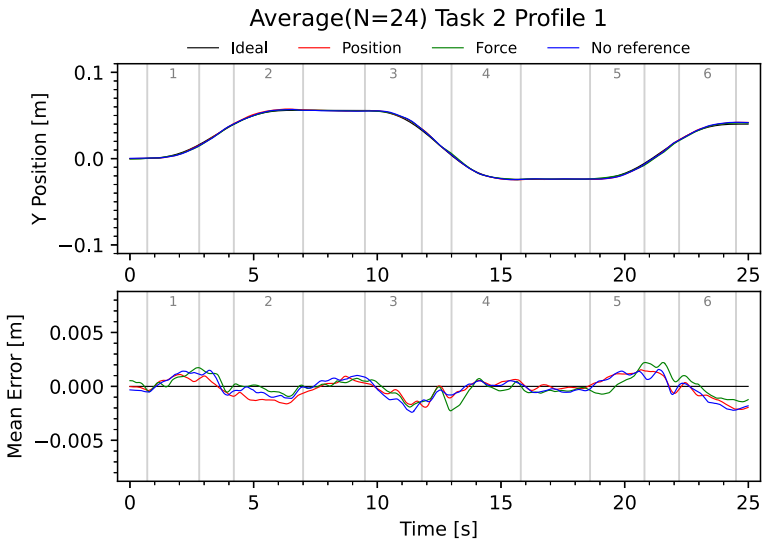

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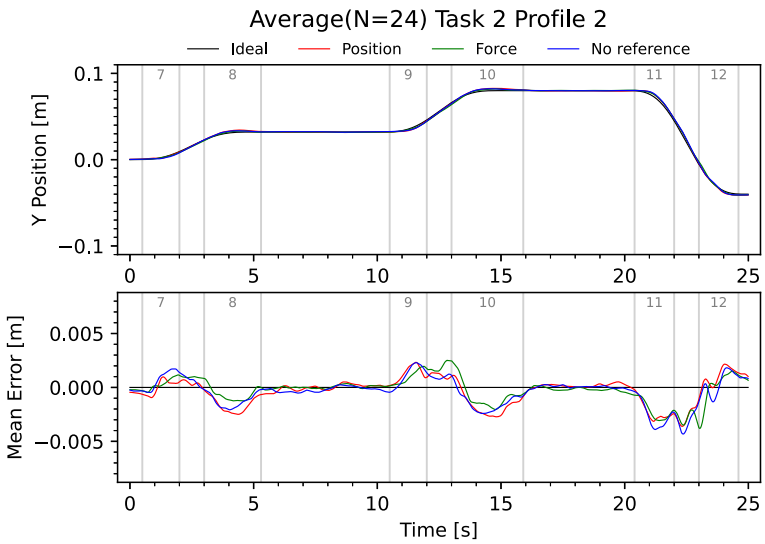

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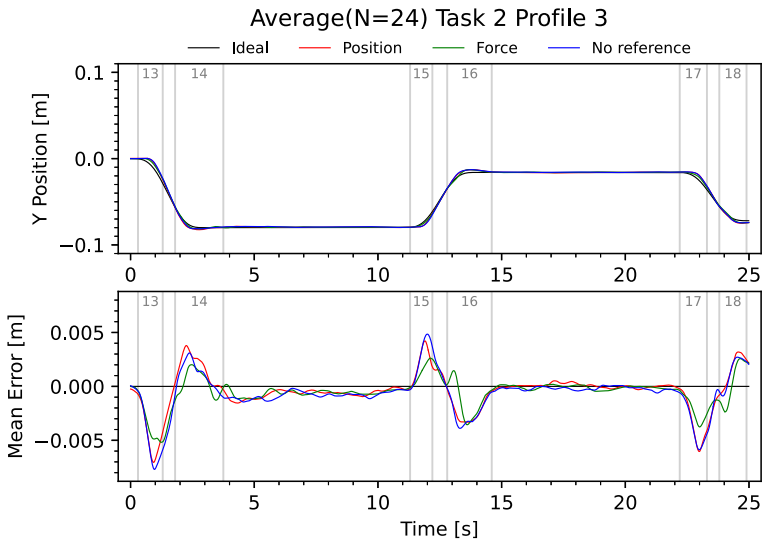

Figure A.9

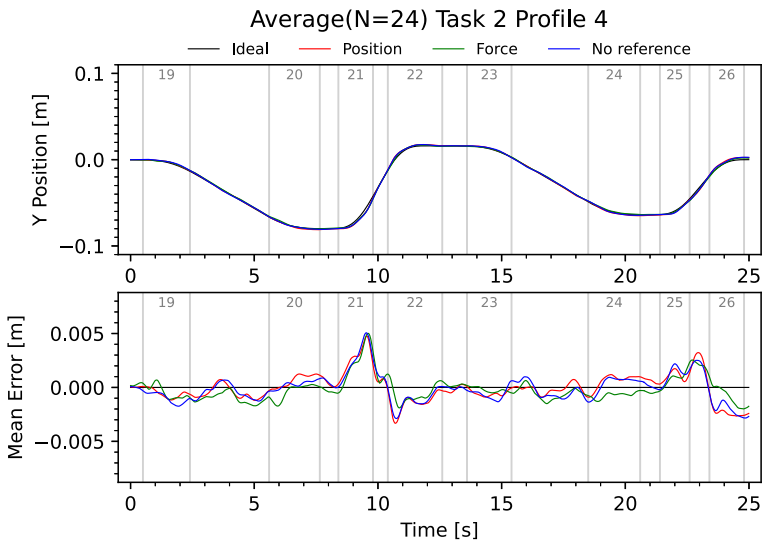

Figure A.10

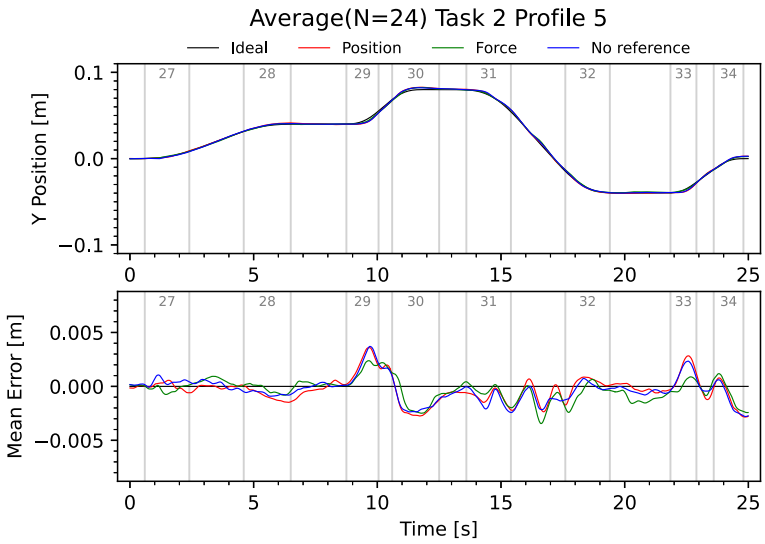

Figure A.11

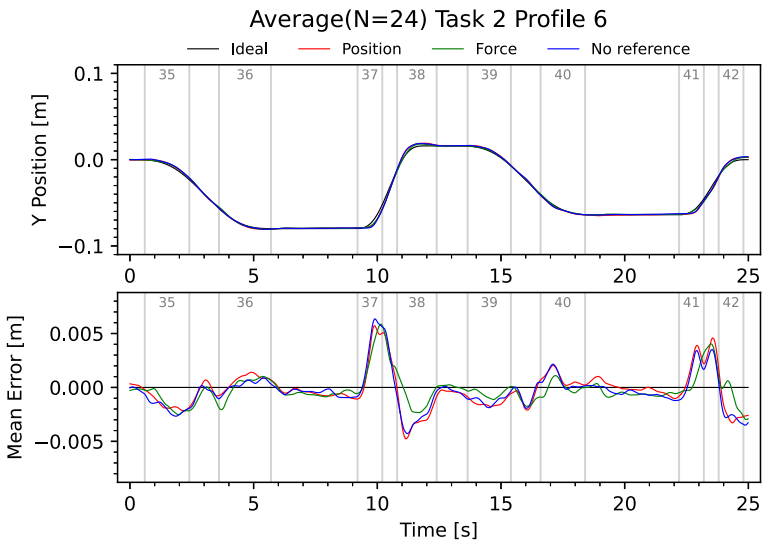

Figure A.12

	Section	**Max. acceleration** $\times 10^{-3}[m/s^2]$	**Max. force [N]**
Low	28	6.12	11.62
	27	6.12	11.62
	2	8.59	16.31
	1	8.59	16.31
	7	9.62	18.27
	8	9.62	18.27
	19	9.66	18.35
	23	9.66	18.35
	20	9.66	18.35
	24	9.66	18.35
	6	9.81	18.64
	5	9.81	18.64
	4	12.3	23.31
	3	12.3	23.31
Medium	9	14.4	27.41
	10	14.4	27.41
	40	16.7	31.72
	36	16.7	31.72
	39	16.7	31.72
	35	16.7	31.72
	32	18.4	34.87
	31	18.4	34.87
	33	24.5	46.49
	34	24.5	46.49
	30	24.5	46.61
	29	24.5	46.61
High	25	30.1	57.10
	26	30.1	57.10
	11	36.1	68.52
	12	36.1	68.52
	21	45.1	85.65
	22	45.1	85.65
	18	46.7	88.82
	17	46.7	88.82
	16	53.4	101.50
	42	53.4	101.50
	15	53.4	101.51
	41	53.4	101.51
	14	66.8	126.88
	13	66.8	126.88
	38	80.1	152.26
	37	80.1	152.26

Table A.1 The selected 42 sections for evaluation sorted by their maximum acceleration and force.

Informed consent

Participant Code: ☐☐ - ☐☐ - ☐☐ - ☐☐

First 2 letters of mother's *first name* | First 2 letters of father's *first name* | Month of mother's birth | Month of father's birth

Subject Number (SN): _____ (leave blank)

Evaluation study: Workload Perception in Virtual Reality

Informed Consent

1. In the current study, the investigators explore the effects of improved depth perception in a virtual reality setup. The study will take about 1h and you will be ask to wear a headset throughout the experiment. During the experimental session, you will be ask several times to rate different experiences like e.g. your perceived workload.
2. As with any simulation study in which a headset is worn, it cannot be ruled out that effects of simulator sickness may occur after prolonged use of the headset. If you experience symptoms such as dizziness, nausea, disorientation or eye pain, please inform the investigator immediately.
3. I was informed verbally and written about the scientific research appropriately. I declare to participate voluntarily and complimentarily in this evaluation study. I can withdraw from the experiment at any time without any disadvantages resulting from the withdrawal.
4. I am obliged to handle the technical equipment with care and follow the instructions of the experimenter.
5. The experimenter assures to store the collected data anonymously and confidentially in a digital format[1] so that external persons are not able to identify which participant yielded which data. Collected data is analyzed for scientific research purposes. **I agree that the person-related data and further data collected in the study are recorded and analyzed.**
6. I was informed that I could demand the deletion of my data at any time.

I read and understood this clarification.

DLR Oberpfaffenhofen, _____ _____

(Date) (Signature participant)

_____

(Signature examiner)

[1] Primary data of a publication should be stored and accessible for at least 10 years according to the *Deutsche Forschergemeinschaft*.

Demographic questionnaire

VP. Nr.: _____
Date: _____
Time:_____

VP Code: ☐☐ ☐☐ ☐☐ ☐☐

First two letters of mother's prename	First two letters of Father's prename	Month of mother's birth	Month of father's birth

Demographic Questionnaire

Age: _____ **Sex:** male ☐ female ☐ other ☐

Profession: _____

Did you work with a force feedback device prior to this study?

no ☐ yes ☐
If yes, in which context did you use it? _____

Do you have experience with VR applications? (VR=Virtual reality)

No ☐ Yes ☐

If yes, how much experience do you have?
Very little Very much
☐ ☐ ☐ ☐ ☐

How many hours a week do you spent in a dynamic system (e.g., driving a car or biking (with side winds), water sports, piloting, robot dynamics, etc.)? ☐

How many hours a week do you spent on playing video games? ☐

How many hours a week do you spent on working with 3D-design software? ☐

Did you ever feel sick within a simulation environment?
No ☐ Yes ☐

Do you wear glasses or contact lenses?
No ☐ Yes ☐

Do you have trouble recognizing colors?
No ☐ Yes ☐

Do you have trouble perceiving spatial depth?
No ☐ Yes ☐

Are you left or right-handed?
Left-handed ☐ Right-handed ☐

Comments/ Problems during experiment:

_____
_____

Post-condition questionnaire

VP Nr.:_____ **Condition: _ / 3**

Post-block Questionnaire

Fast Cybersickness – How sick do you feel?

Very sick																				Very good

NASA-Task Load Index

Mental Demand How mentally demanding was the task? Was it simple or complex?

very low/ simple — very high /complex

Physical Demand How physically demanding was the task? Was it easy or strenous

very low/ easy — very high /strenous

Temporal Demand How hurried or rushed was the pace of the tasks? Was it slow or rapid?

very low/ slow — very high /rapid

Performance How successful were you in accomplishing what you were asked to do?
(1= Perfect Success; 20 = Total failure)

Perfect — **Failure**

Effort How hard did you have to work to accomplish your level of performance?

very low — very high

Frustration How insecure, discouraged, irritated, stressed, and annoyed were you?

very low — very high

VP Nr.:_____ **Condition: _ / 3**

System Usability Scale

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

VP Nr.:_____ **Condition: _ / 3**

Presence IPQ

Now you'll see some statements about experiences. Please indicate, whether or not each statement applies to your experience. If a question is not relevant to the virtual environment you used, just skip it. You can use the whole range of answers. There are no right or wrong answers, only your opinion counts.
You will notice that some questions are very similar to each other. This is necessary for statistical reasons. And please remember: Answer all these questions only referring to this one experience.

How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?

extremely aware							not aware at all
-3	-2	-1	0	+1	+2	+3	
			moderately aware				

How real did the virtual world seem to you?

completely real							not real at all
-3	-2	-1	0	+1	+2	+3	

I had a sense of acting in the virtual space, rather than operating something from outside.

fully disagree							fully agree
-3	-2	-1	0	+1	+2	+3	

How much did your experience in the virtual environment seem consistent with your real world experience?

not consistent							very consistent
-3	-2	-1	0	+1	+2	+3	
			moderately consistent				

How real did the virtual world seem to you?

about as real as an imagined world							indistinguishable from the real world
-3	-2	-1	0	+1	+2	+3	

I did not feel present in the virtual space.

did not feel							felt present
-3	-2	-1	0	+1	+2	+3	

I was not aware of my real environment.

fully disagree							fully agree
-3	-2	-1	0	+1	+2	+3	

VP Nr.:_____ **Condition: _ / 3**

In the computer generated world I had a sense of "being there"

not at all very much

-3 -2 -1 0 +1 +2 +3

Somehow I felt that the virtual world surrounded me.

fully disagree fully agree

-3 -2 -1 0 +1 +2 +3

I felt present in the virtual space.

fully disagree fully agree

-3 -2 -1 0 +1 +2 +3

I still paid attention to the real environment.

fully disagree fully agree

-3 -2 -1 0 +1 +2 +3

The virtual world seemed more realistic than the real world.

fully disagree fully agree

-3 -2 -1 0 +1 +2 +3

I felt like I was just perceiving pictures.

fully disagree fully agree

-3 -2 -1 0 +1 +2 +3

I was completely captivated by the virtual world.

fully disagree fully agree

-3 -2 -1 0 +1 +2 +3

VP Nr.:_____ **Condition: _ / 3**

Virtual Embodiment Questionnaire (VEQ)

Instructions

Please read each statement and check the relevant response to indicate how strongly you agree or disagree with each statement (1 through 7). There are no right or wrong answers. Answer spontaneously and intuitively.

Acceptance/Body Ownership	*Strongly disagree* 1	*Disagree* 2	*Somewhat disagree* 3	*Neither agree nor disagree* 4	*Somewhat agree* 5	*Agree* 6	*Strongly agree* 7
AC1 myBody It felt like the virtual body was my body.	o	o	o	o	o	o	o
AC2 myBodyParts It felt like the virtual body parts were my body parts.	o	o	o	o	o	o	o
AC3 humanness The virtual body felt like a human body.	o	o	o	o	o	o	o
AC4 belongsToMe It felt like the virtual body belonged to me.	o	o	o	o	o	o	o

Control/Agency	*Strongly disagree* 1	*Disagree* 2	*Somewhat disagree* 3	*Neither agree nor disagree* 4	*Somewhat agree* 5	*Agree* 6	*Strongly agree* 7
CO1 myMovements The movements of the virtual body felt like they were my movements.	o	o	o	o	o	o	o
CO2 controlMovements I felt like I was controlling the movements of the virtual body.	o	o	o	o	o	o	o
CO3 causeMovements I felt like I was causing the movements of the virtual body.	o	o	o	o	o	o	o
CO4 syncMovements The movements of the virtual body were in sync with my own movements.	o	o	o	o	o	o	o

Change	*Strongly disagree* 1	*Disagree* 2	*Somewhat disagree* 3	*Neither agree nor disagree* 4	*Somewhat agree* 5	*Agree* 6	*Strongly agree* 7
CH1 myBodyChange I felt like the form or appearance of my own body had changed.	o	o	o	o	o	o	o
CH2 echoHeavyLight I felt like the weight of my own body had changed.	o	o	o	o	o	o	o
CH3 echoTallSmall I felt like the size (height) of my own body had changed.	o	o	o	o	o	o	o
CH4 echoLargeThin I felt like the width of my own body had changed.	o	o	o	o	o	o	o

Procedure Checklist

VP Nr.:_____ Checklist: Dynamic Guiard - Study

WHERE	**WHAT**	**DONE**	**NOTES**
HMD	Desinfizieren		
HMD	Linse reinigen		
Lambda	Reinigen		
Omega	Reinigen		
Handfixierung	Reinigen		
Benutzer*innen die Studie kurz erklären	**Auf Deutsch:** Du benutzt mit deinen Händen beide Maschinen und wir schauen, wie gut es klappt. Wir testen das System. Wenn was nicht gut läuft, dann liegt es nicht an dir. Es wird noch ein kurzes Training geben. **In English:** You use both machines with your hands and we see how well it works. We test the system. If something doesn't go well, it's not your fault. There will still be a short training.		
Fragebogen	Informed Consent		
Fragebogen	Demographic questionnaire		
Benutzer*innen den Aufbau kurz erklären	**Auf Deutsch:** Versuchsaufbau: Omega (nur Feedback), Lambda (nur Kontrolle), HMD (Vorführung mit Bild der VR-Umgebung) **In English:** Experiment setup: Omega (only feedback), Lambda (only control), HMD (showcasing with image of VR environment)		

FAMILIARIZE WITH SETUP			
Benutzer	1. Nutzer zum Hinsetzen bitten. 2. Stuhl kann nach vorne/hinten verschoben werden, muss aber mittig sein.		
Omega, Benutzer und Handfixierung	Omega zeigen 1. Ohne Handfixierung 2. Mit Handfixierung: a. Omega ausschalten b. EINSTELLEN c. Danach wieder einschalten! 3. Unterschiedliche Ablagen (Ellenbogen, Fixierung usw.) probieren		
Lambda, Benutzer	Lambda zeigen 1. Finger drücken! 2. Am Laptop die Bewegung zeigen 3. Ablage nur bei Pause!		
HMD, Benutzer	HMD initialisieren 1. HMD halb aufsetzen, nicht komplett 2. Kurz nach vorne (SMILE anschauen), HMD komplett aufsetzen und initialisieren (3. Knopf v. R) 3. MEHRMALS üben!		
HMD, Benutzer	Schärfe / Augenabstand prüfen		
Benutzer	Lambda und Omega in die Hände nehmen		
Benutzer	Mit Geräten (IDLE) warm werden. Auch mit den unterschiedlichen		
Dashboard	BENUTZERZAHL EINGEBEN!		

4x Wiederholen			
CONDITION (1,2,3) + TASK (1,2) - TRAINING			← 4x Done!
Order Checklist / Dashboard	Condition/Task aus der Liste/Dashboard entnehmen		
Dashboard	Training Modus auswählen, Initialisieren		
Setup anpassen	Setup anhand Condition (1,2,3),Task (1,2) herrichten		
Benutzer	Auffordern Lambda und Omega in die Hände zu nehmen		
Benutzer	Kurze Erklärung 1. Task a. Task 1: Hold, b. Task 2: Track 2. Condition Kraft/Position/Nichts - z.B. Wind		
HMD	Nur nach Ablegen! Nach vorne schauen, HMD initialisieren!		
Dashboard	Starten, fertig sobald 3D Model verschwindet		
Dashboard	Stoppen		Optional
Benutzer	Hände weglassen, sobald fertig		

36x Wiederholen			
CONDITION (1,2,3) - STUDIE TASK (1,2) Profile 1-6		← Order Checklist!	
LN Manager	Logging Start/Stop nach 3 Tasks		
Order Checklist / Dashboard	Task aus der Liste/Dashboard entnehmen und abgleichen		
Order Check	Prüfe, ob Training notwendig ist		
Dashboard	Studien Modus auswählen, Initialisieren		
HMD	Nur nach Ablegen! Nach vorne schauen, HMD initialisieren!		
Benutzer	Auffordern Lambda und Omega in die Hände zu nehmen		
Benutzer	Zur Markierung gehen (orange) → Dann erst READY!		
Dashboard	Starten, Fertig sobald 3D Model verschwindet **Optional:** Stoppen + Reset		
Order Checklist / Dashboard	**5x Wiederholen** und in Order Checklist wegstreichen, im Dashboard: Initialisieren / Starten		
Benutzer	Hände weglassen, sobald fertig		
CONDITION (1,2,3) - FRAGEBOGEN			← 3x Done!
Benutzer	Post-Block		

STUDY - POST CONVERSATION			
Notizblatt	Notizbuch und Aufnahmegerät bereitlegen		
Benutzer	Offene Fragen stellen **Auf Deutsch:** Was denkst Du im Moment über das Experiment? Hast Du einen Unterschied zwischen den verschiedenen Bedingungen wahrgenommen? (Was war hilfreich? Hat etwas gestört?) Wie haben sich die unterschiedlichen Feedback Typen auf die Interaktion ausgewirkt? **In Englisch:** What are your thoughts about the experiment at the moment? Have you sensed a difference in the various conditions? (What was helpful? Did something bother you?) How did the various feedback impact your interaction?		

Subtask Checklist

Check Task Order: Dynamic Guiard - Study

Top-Down: Subtask (S) / Condition (C) / Task (T) / Profile (P)

Beachte Training bei ROT!!!
Abspeichern bei BLAU/ROT

Participant 1 - VP Nr.:_____

	Condition												Condition												Condition											
S	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
C	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3
T	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2
P	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6

Participant 2 - VP Nr.:_____

	Condition												Condition												Condition											
S	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
C	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3
T	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1
P	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6

Participant 3 - VP Nr.:_____

	Condition												Condition												Condition											
S	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
C	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
T	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2
P	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6

...

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Erklärung

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbstständig angefertigt, alle Zitate als solche kenntlich gemacht sowie alle benutzten Quellen und Hilfsmittel angegeben habe.

München, den 7. September 2023 DBurandt

Daniel Burandt