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Investigating Weight Distribution in Virtual Reality Proxy Interaction

Master's Thesis

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Abstract

Proxy interaction is a way to add haptics to interactive virtual realities. Here, users interact with physical models, called proxies, that physically represent virtual objects in the virtual environment. Previous research has investigated several properties of proxy objects and their influence on proxy interaction. However, the role of a proxy's weight distribution in virtual reality interaction is still understudied. This thesis investigates the influence of proxy weight distribution and corresponding visual-haptic discrepancies on virtual reality proxy interaction and the perception of virtual objects. In two experiments, participants interacted with virtual objects represented by physical proxies of different weight distributions. It could be shown that weight distribution is an influential proxy property with great potential to enhance future interactive virtual reality experiences involving haptics. Weight shift direction was found to be the most important factor for perception, especially for perceived realism. Weight distribution discrepancies were shown to cause errors during interaction. In addition to that, it was shown that using the weight distribution of the proxy, other properties of virtual objects like length and weight can be simulated on a perceptual level. The findings fill a gap in the research on proxy properties and can help to develop versatile proxy objects that change their weight distribution to enable enhanced virtual reality experiences.

Contents

Chapter 1
Introduction

1.1 Motivation

Virtual Reality is a technology that most people already know for many years without having much or any first-hand experience. This is due to science-fiction authors that made *Virtual Reality* a prominent feature in many science-fiction stories. While in science-fiction, the heroes can unproblematically use the *Virtual Reality* technology to dive into and interact with *Virtual Environments*, things get a bit more complicated in reality.

Now, that *Virtual Reality* is emerging from pure science-fiction to become an experiential and maybe even a ubiquitous technology, new problems arise. As *Virtual Reality* can be used for entertainment (gaming, movies, etc.), training, education, visualization, manufacturing, therapy, research and more, each different field comes with its own specific challenges. Besides these, fundamental research is necessary in the first place to find solutions to basic challenges encountered in all application areas.

As the problem of seeing and hearing the virtual world is about to be solved by modern *Virtual Reality* goggles, the next modality to be included in *Virtual Reality* systems is *touch*. As passive observation will not be enough in the long term, solutions that let the user interact with the virtual world in a natural way become crucial. One possible way to make *Virtual Realities* tangible is to use real world physical props, also called proxies, that are coupled to virtual objects. The user can then interact with virtual objects by interacting with the corresponding representative prop. These props are typically no exact replicas of the virtual objects and hence a certain amount of mismatch is omnipresent. To develop predictable systems it is of course necessary to know about the influence of this mismatch on the user's behavior in the *Virtual Reality* and his perception of the virtual object. This motivated researchers to study the effect of several proxy properties and the corresponding mismatches on the user. But so far, no research has investigated the influence of a proxy's *weight distribution* on *Virtual Reality* interaction.

This thesis aims to fill this gap and researches the influence of the *weight distribution* of proxy objects on the user's behavior and perception of objects in *Virtual Realities*.

1.1.1 Virtual Reality

*"**Definition:** Virtual reality is a high-end user-computer interface that involves realtime simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell and taste"*
- Burdea and Coiffet, 2003 [1]

Virtual Reality (VR) allows people to experience immersive virtual worlds in a way that makes them feel as if they are *in* them. During such an experience, multiple channels of the user's perceptual system such as the visual, auditory and haptic channel are stimulated by the virtual world [2]. These stimuli are triggered by computer systems simulating the *Virtual Environment* (VE).
The most prominent channel to be stimulated in VR experiences is the visual perception. Beyond monoscopic renderings of the virtual world, VR systems frequently present the simulated world by means of stereoscopic *Three-Dimensional* (3D) renderings to the user. These computer generated images are then commonly displayed to the user either using VR *Head Mounted Display*s (HMDs) or projection screen set-ups. In addition to the visual, the auditory channel is commonly stimulated by surround sound technology typically implemented with headphones or sound systems. This allows the user to perceive the VE's sounds and to explore the virtual world in a more natural way. The combination of visual and auditory stimulation already gives good impressions and suits well for passive VR applications in which observation is the primary task. But as soon as the VE becomes more interactive and interaction with objects in the VE is necessary, haptic stimuli come into play. The ability to touch objects is ubiquitous in our everyday life and thus a feature no interactive VR application must miss [3].
Besides the already mentioned sensorial channels, many more interesting perceptual systems like e.g. temperature perception, odor perception and gustation can be used to further increase the believability of the illusion and to further strengthen the feeling of presence in order to reach the ultimate goal of a *holodeck*-like [1] simulation.

[1]The *holodeck* is a term from the science-fiction entertainment franchise *Star Trek*. In this fictional universe, *holodeck* rooms are located on board spaceships and able to realistically recreate arbitrary environments visually, auditorily, haptically, olfactorily and gustatorily. It is frequently mentioned to be the ultimate reference for VR technology.

Figure 1.1: Picture of VR research at NASA during the 90s showing a VR-HMD and data gloves of that time [4]

For decades now researchers around the world conduct VR research in order to improve the technology and to investigate the possibilities of VR. While many advances were made in the last years, VR research is not new and many basics have already been developed during the 90s.
But back then, VR hardware was rare, very expensive and in many aspects such as video-resolution, latency and computational power, the technology was much less capable than it is today. So VR has been primarily used for research and in some military and industrial sectors. But the big success in the consumer market did not ensue.
Today, about 20 years later, the public interest in VR technology is bigger than ever before. Driven by the entertainment sector's and other industries' interest in VR, the development of VR-HMDs made big advances in the last years. As a result, the first wave of consumer VR-HMDs is about to hit mass-markets all around the globe at affordable prices.
Besides gaming and other entertainment areas like VR-movies, VR can assist in training for sports, emergency, military and medical personnel [5, 6]. It has the potential to improve assembly processes [7] and it can provide insights into the future by simulating architectural projects and early prototypes. Conversely it can also provide insights into the past, by providing experiences offered at museums and cultural heritages in the edutainment sector [3] and it can even help to treat diseases [8, 9]. In addition to that, VR can be used by researchers of various fields such as medicine or psychology [10]. The areas of application for VR seem countless, but in most of them a passive observation of the VEs is not sufficient. Instead, interaction is vital.
The new VR technology today profits from readily available low-cost high-performance hardware which was not available or not affordable for personal use in the 90s. With today's already huge and ever increasing gaming industry, systems capable of simulating and rendering complex VEs can be found in most

homes. Thus, most things are put on the right track for the big VR success. As it is very likely that in the coming years, VR will find its way into many sectors that can benefit from it, it has the potential to become a ubiquitous technology in the near future.

Figure 1.2: The *Oculus Rift DK 2* used in the experiments of this thesis. It is an example for a modern VR-HMD whose final version is going to be released for consumer markets soon.

1.1.2 Haptic Interaction in Virtual Reality

As in the long term the simulation of visual and auditory VR features is not enough, most VR applications will require smart ways for the user to interact with the virtual world. With gestural interaction, as known from systems such as the *Microsoft Kinect*, being established as a way for embodied interaction, one solution could be to use gestural interaction in VR as well. But as no haptic feedback is provided, this gestural interaction lacks the information gained by humans from touching objects.

Researchers found, that haptic feedback can enhance the user experience and immersion in VR significantly [3,5–7,9,11–19]. The huge research efforts undertaken in the field of haptic technology for VR brought up two main classes of haptic systems: active and passive haptics [15].

In active haptic systems the haptic feedback (force feedback and more subtle tactile feedback) is mediated through devices with active physical actuators controlled by the computer. These devices are typically specialized on a particular kind of feedback or application. While they might perform well for it, they do not yet solve the general problem of haptic feedback in VR completely. Passive haptics, however, are different from active haptics in that they do not use actuators to actively exert forces on the user. Instead, real physical models are used and users can interact with them. These models represent virtual objects and passively provide touch feedback during the interaction through their sole existence. Besides large, immobile, static and rigid models that represent obstacles like e.g. walls [11], smaller mobile models can be used as well, representing interactive objects like e.g. tools. The user can then pick them up to interact with the virtual object. These models are called *proxy objects* or *proxies* [7,9]. Of course, the concepts of active and passive haptics are not mutually exclusive and so, concepts that combine both ideas exist as well [17,20].

1.1.3 Proxy Objects and their Properties

Following the concept of passive haptics, the question arises, how virtual objects can be represented by suitable proxies. To answer the question and to understand what features (like shape, size, weight, material etc.) of proxies are actually important to consider when designing them, a thorough investigation of their properties and effects on perception and user behavior is essential.
The use of only 1-to-1 replica objects is not a desired solution since each interactive virtual object would need to be modeled physically exactly as it is in the virtual world. But this is a quite challenging, complex and expensive task. Thus, it is desired to simulate multiple different virtual objects with a single, and in the best case also simple, real proxy object. In order to develop such general proxies, it is unavoidable to investigate the qualities and capabilities of a proxy's different features. Moreover, it is important to know, which effects certain proxy properties have on the user's perception and behavior in the VE. In conjunction with that, it is crucial to study the roles that certain kinds of mismatch between virtual and real objects play. The research community investigated some proxy properties in the past and some of the questions above could already be answered for certain proxy features. Among the already considered proxy properties are a proxy's *shape* [9,21–23], *size* [9,23], *absolute weight* [9], *temperature* [9,19], *material* [9,22] and *function* [9]. But up to now, a study of the related literature could not bring up any results concerning the influence of another property that strongly affects how people interact and engage objects in reality: the *weight distribution* (especially the *Center of Mass* (CM) location) of the proxy.

This thesis aims to fill this gap by investigating the influence the weight distribution of proxy objects has on user perception and behavior. The results of these investigations shed light on how the weight distribution can be used to build better and more generic proxy objects facilitating realistic VR experiences.

1.2 Research Goals

It has been promoted in the past, that researchers should *"bring the three modalities together in VEs and [...] study their interactions in affecting human perception and performance"* [2] [3]. This thesis can be seen as a contribution to this goal. As already introduced, the *weight distribution* of proxy objects is a feature, that was found understudied. The main motivation for this thesis is to do the next step in the investigation of proxy properties by taking a closer look on the influence of a proxy's *weight distribution* on user perception and behavior.

The main hypotheses of this work are, that a proxy's *weight distribution* has an effect on the user's **behavior** during the interaction in the VE and that it affects the user's **perception** of the virtual objects he interacts with. These points have been investigated experimentally in this work. In addition, two concepts that exploit the proxy *weight distribution* to make proxies more general [3] are introduced as part of the conducted experiments.

The following list summarizes the main concrete research goals of this thesis:

Goal 1: Investigation of the influence of the proxy *weight distribution* **on user behavior** during the interaction with virtual objects.

- **a)** Investigation of the influence of the proxy *weight distribution* and the visual-haptic stimuli discrepancy (also called mismatch) on user behavior and the order of magnitude of these effects.
- **b)** Investigation of the role of directional weight shift.

Goal 2: Investigation of the influence of the proxy *weight distribution* **on the user's perception** of virtual objects.

- **a)** Investigation of the influence of the proxy *weight distribution* on perceived object *form*
- **b)** Investigation of the influence of the proxy *weight distribution* on perceived object *weight*.

Both the influence on the user's **behavior** (**Goal 1**) and the influence on the user's **perception** (**Goal 2**) can be seen as orthogonal dimensions. Hence they are investigated separately.

To study the effect of the proxy *weight distribution*, an experimental approach was chosen. Users participating in the experiments were therefore immersed in a VR system. The development of this VR system was part of the work for this thesis.

[2] *"Three modalities:"* visual, haptic and auditory dimension.

[3] With *general* meaning the ability of a single proxy object to believably simulate/represent multiple different virtual objects.

In order to conduct the experiments, the VR system should allow users to stand upright in VEs, it should provide auditory feedback and allow users to interact in realtime with virtual objects in the VE using physical proxies.

1.3 Outline

In the following, the structure of the remaining parts of this thesis is outlined. The next chapter overviews some **Related Work** with sections about the **Reality-Virtuality Continuum**, **Substitutional Reality**, **Haptics in Virtual Reality**, **Immersion** and **Human Perception**. Following up, the chapter **Concept** will provide an **Overview** over the general design of the experiments. The section **Implementation** will describe the **Virtual Reality System** and the **Proxy Objects** used. The chapter **Experiments** will then treat the two main experiments that were conducted in some more detail and the following chapter **Results** will then summarize the obtained results. The **Discussion** chapter subsequently interprets the results and further discusses the topic. Eventually, the chapter **Conclusion and Outlook** comprises the **Conclusion** of the thesis and provides some **Recommendations for Future Work**. A **List of Tables**, **List of Figures**, **List of Abbreviations** and the **Bibliography** can be found at the end of the thesis.

Chapter 2
Related Work

This chapter will provide insights into past research related to the investigation of the proxy weight distribution. First, some basic VR-related concepts and terms are introduced in the section **Reality-Virtuality Continuum**. Moreover, the developed VR system used to conduct the experiments is classified in this section. The second section then reviews the concept of **Substitutional Reality** and introduces a classification model for the mismatch between real and virtual objects. Following up, the section **Haptics in Virtual Reality** introduces the field of computer haptics in general and overviews the most important concepts concerning VR haptics. The section further includes a review of the current state of research on proxy properties and their influence on VR interaction. In the section **Immersion**, some important results on the phenomenon of believing to be really inside a VE are summarized. Eventually the section **Human Perception** will give some detail on how haptic feedback is actually perceived by humans. In this context, it will review some important result on the perception of different weight distributions which inspired the experiments described in the following chapters.

2.1 Reality-Virtuality Continuum

In the context of this thesis, different terms like *Virtual Reality* (VR), *Augmented Reality* (AR), *Mixed Reality* (MR) and some more are frequently used. This section will clarify the meaning of and differences between these terms. Additionally, it will classify the setup this research applies to in some more detail. In this way, it also classifies the system developed for this thesis.

Colloquially, a system is called *Virtual Reality* (VR) system when the user of the system only sees the *Virtual Environment* (VE) through a *Head Mounted Display*

(HMD) blending out the real environment. But in the scientific context, classifications exist that classify different kinds of systems more exactly.
Milgram published a very important classification of different kinds of systems based on their degree of mixture of real and pure virtual aspects [24, 25]. In the original publication, the focus lay primarily on the display of a mixture of real and virtual visual content. But today, where VR technology is increasingly concerned with higher dimensional VR (including e.g. the dimension of VR haptics), some researchers apply this taxonomy on more than just the visual dimension [15]. Since most VR experiences consist of the stimulation of more than just the visual perception, Milgram's taxonomy can be extended and used in a way that covers additional dimensions as well, e.g. the auditory and haptic dimension. In his taxonomy, it makes a difference, whether each and every stimulus perceived by the user is computer modelled and computer generated or whether some stimuli are unmodelled in the computer and instead come from reality. The amount of computer modelled knowledge is called *Extend of World Knowledge* (EWK). Milgram identified two extremes: *Reality* and *Virtuality* (VR).
Reality means that everything the user perceives are real stimuli originating from the real world, also called *Real Environment* (RE). It also means that nothing the user interacts with or perceives is actually modelled in the computer or computer generated. In Figure 2.1, *Reality* is illustrated as the left end.
Virtuality, or VR, on the other hand, is the complete opposite of *Reality*. In pure VR, everything the user perceives and interacts with is pure virtual content from the *Virtual Environment* (VE) which is completely modelled in the computer and computer generated. Not a single perception from reality is present, really everything is virtual and modelled. In Figure 2.1, *Virtuality* is depict at the right end.
Milgram further identifies both extremes to not be alternatives, but rather to be opposite poles of the *Reality-Virtuality* (RV) continuum. In between them is a continuous space of so called *Mixed Realities* (MRs). A *Mixed Reality* (MR) is defined as anything between (but excluding) pure *Reality* and pure *Virtuality* in the RV continuum. In other words, any mixture where some stimuli are reality-based

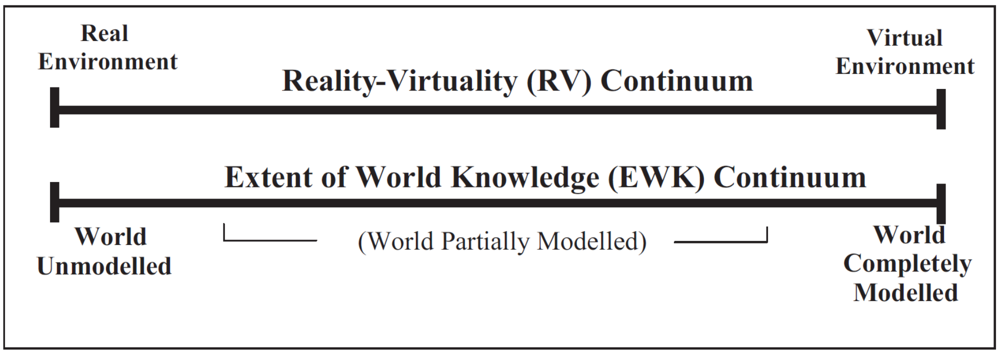

Figure 2.1: The Reality-Virtuality (RV) Continuum in parallel with the Extend of World Knowledge (EWK) Continuum [24]

and others are virtual is classified as MR. Systems close to *Reality* are different, however, from those close to *Virtuality* as they let the user primarily perceive reality-based impressions and only use some virtual stimuli to augment the reality. The user can for example see his real surroundings while some small virtual texts or images are rendered into the RE. As the content primarily perceived is still reality-based but augmented by some virtual augmentations, this class of MR systems is called *Augmented Reality* (AR). Conversely, when the user primarily perceives virtual content and this virtual content is augmented with some real stimuli, the system is classified as *Augmented Virtuality* (AV). An example would be an application in which the user sees primarily the virtual world through a VR-HMD but some specific aspects of reality (e.g. parts of the real world surrounding) are blended into the view. Milgram's taxonomy is summarized in the following figure depicting the complete *Reality-Virtuality* (RV) continuum:

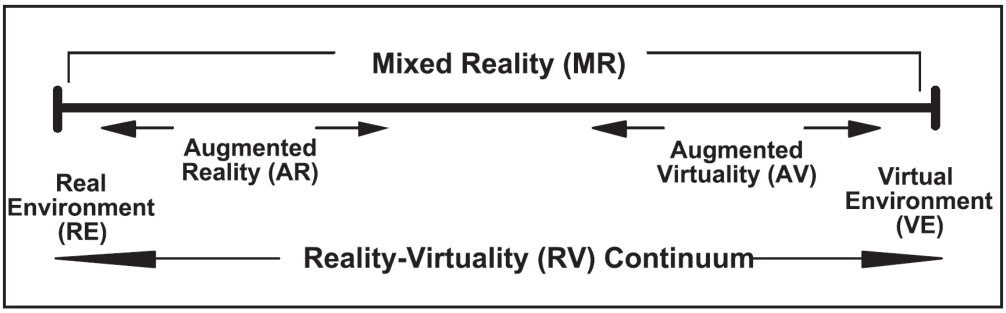

Figure 2.2: The Reality-Virtuality Continuum including Mixed Reality [24]

Classifying applications in which the user is immersed in a *Virtual Environment* (VE) while interacting with virtual objects using real proxy objects, is similar to the example described above. The primarily perceived content, e.g. the visual environment and the sounds, is pure virtual and completely computer-modelled. Thus it must be close to the *Virtuality* end of the RV continuum. The stimuli are not all virtual though, since the haptic stimuli are real and completely unmodelled in the computer system as the user interacts with real physical proxy objects. As a result of this investigation, interactive VR systems with proxy object interaction, including the system developed for this thesis, can be classified as *Augmented Virtuality* (AV), which is a form of *Mixed Reality* (MR).

An interesting example of *Augmented Virtuality* (AV)-applications, besides the system developed for this thesis, is the concept of selective engagement-dependent AV [26]. It uses reality-based visual augmentation of the primarily virtual display. The authors propose to let the user or the system automatically control the position in the RV continuum during the VR experience. Their paper shows ways to selectively blend parts of reality into the virtual view. The blending is thereby engagement-dependent. This means the system infers when and how much reality is blended into the virtual display based on the user's engagement with real objects. As an example, this could work as follows: when a user engages his keyboard to type, the keyboard and his hands are blended into the virtual view in order to enhance typing performance. With this technique, the authors try to solve a set of important usability issues commonly reported by users of VR-HMDs whilst minimizing the impact on immersion. These issues comprise e.g. the awareness of other people in the environment, their proximity and problems in interacting with the real world surrounding, e.g. taking a drink, or with real world interfaces, e.g. using the keyboard.

2.2 Substitutional Reality

A concept that couples the *Real Environment* (RE) and the *Virtual Environment* (VE) in a systematic way is introduced in Simeone et al.'s paper [9]. The paper promotes the idea of proxy interaction in VR and investigates the influence of a broad variety of proxy properties on immersion and user engagement. The authors introduce a MR concept, called *Substitutional Reality* (SR), that links the RE of the user, e.g. his home, directly to the VE, e.g. the level of the game he plays[4]. Here, each object in reality is mapped to a virtual object in the virtual scene implementing the approach of passive haptics and real world proxies. An example in their paper, depict in Figure 2.3, links a couch in the VR lab to a futuristic cosy onboard a spaceship or a wooden bench inside a medieval environment. The authors note that *"by substituting each physical element with a virtual counterpart, a VE is able to leverage physical properties to create convincing bodily experiences"* [9].

Figure 2.3: An example of a Real Environment (middle) and two Substitutional Environments (left;right) [9]

[4]The *Substitutional Reality* (SR) concept introduced by Simeone et al. [9] is not to be confused with the *Substitutional Reality* (SR) system introduced by Suzuki et al. [10]. The system by Suzuki et al. demonstrates how VR technology can be used in neuroscience and psychology research. It is used to study *"the mechanisms of metacognitive functions and psychiatric diseases"* [10]. Their SR system allows to switch between the display of real live scenes (the actual reality, also known as video-passthrough) in which users are physically present and the display of prerecorded scenes. The switching happens in a way that users cannot distinguish the reality gap. In their experiments, participants successfully believed that they experienced live scenes when in fact prerecorded scenes were shown to them.

The mapping from physical object to virtual object may vary in terms of mismatch, or also called discrepancy, between the objects. The paper introduces a layered model of modification which describes and classifies the mismatch. This model is especially interesting with regard to VR proxy object design as it can be used to analyze, communicate and design the degree of mismatch between virtual object and real counterpart.
The introduced layers are:

- *Replica*:
  The virtual model exactly matches the real object.
- *Aesthetic*:
  The virtual model differs from the real object just in an aesthetic way (e.g. different color).
- *Addition/Subtraction*:
  The shape is altered.
  - *Subtraction*:
    The virtual model might lack some feature the real object has (e.g. a mug might lack a handle).
  - *Addition*:
    The virtual model might possess features not present in reality (e.g. a mug might be bigger or it might have more handles than the real one).
- *Function*:
  The function and the possible interactions of the real and the virtual object differ. Things that can be done with the real object are not communicated by the virtual appearance or, even more disturbing for the user, things that can be done with the virtual model can not be done with the real world proxy object.
- *Category*:
  The most extreme kind of mismatch. Virtual and real objects are barely related. Both might differ in shape, function and other properties.

It is apparent from the descriptions, that the introduced layers approximately describe levels of increased mismatch.

As the accepted discrepancy of a real-virtual pairing increases, so does the number of possible substitutions. And vice versa, if the accepted discrepancy minimizes, the amount of suitable proxy objects diminishes. In order to be applicable, the challenge is to find suitable but still to some degree general proxy objects able to represent a number of virtual objects believably.
To study the influence of the introduced discrepancy types on immersion and user engagement, the authors conducted two user studies. In the first study, they registered a real mug with various virtual objects illustrating the different kinds

of discrepancy. Thus here, the visual representation of the object changed while the physical object remained unaltered. In the second study, the virtual object remained the same, namely a lightsaber which participants used to hit targets, but the proxy object changed. They used a 1-to-1 replica, an umbrella and a torch as substitutions. Their results are summarized in more detail in the next section about haptics and proxy properties. They show that the discrepancy between virtual object and proxy can have significant influence on immersion and the level of user engagement. As a general result the authors state that *"in the absence of exact replicas, those objects that present similar affordances [...] in the parts most likely to be interacted with, are the best candidates for substitution"* [9]. They also describe that their users *"reported the mismatch to become significant when the virtual appearance suggested variations in terms of tactile feedback, temperature, and weight not portrayed by the physical proxy"*. At this point, further research is necessary, in order to investigate the roles of the weight distribution and the discrepancy originating from mismatches in the CM location.

2.3 Haptics in Virtual Reality

2.3.1 Computer Haptics in General

Reasons for the Integration of Haptics

"Haptic feedback is one of many available interaction mediums, with special properties that suit it uniquely to some contexts" - MacLean [16].

Haptic interaction is ubiquitous in everyday life. People use their hands to explore and manipulate objects as they interact with them and they gain a huge body of information from the haptic sensation. With haptic perception, people assess an object's shape, its dynamic properties, the material, the size, the temperature, the weight and more to infer how to approach and handle an object. The problems that occur when no haptic feedback is provided in interactive VR systems are likely to negatively influence immersion. They are *"detracting from the realism of the VE"* [12]. Common problems are e.g. that the tracked hand of the user reaches through or inside an object as the user tries to pick it up. Without haptic feedback, objects are not solid, they do not have a weight or a mass and thus they do not obey basic physical laws [12].

As described by MacLean [16], haptic sensation is multi-parametered with parameters such as e.g. force, pressure, moisture, temperature, spatial and temporal textures. Each parameter can further be subdivided and a huge amount of different sensations results. These range from the complex sensation of fur to the sensation of glass or stone, cork or flowing water. As people interact, they experience different haptic sensations. They learn to associate their haptic impression

with the object or material that they see while touching. When people encounter familiar objects, they already have some expectations of how the objects will feel like. In case they encounter new and unknown materials or objects, they infer how it could feel based on the input of other senses like the visual or auditory and their past experience with similar objects. In the real life, the motivations for touching are broad. People touch to do, to probe, to communicate, to poke, to verify, to monitor and to judge something. Moreover, touch can be triggered in order to enjoy comfort or to connect with something or somebody on some physical or emotional level [16].
When building believable and immersive virtual worlds it is important to keep in mind that these motivations to touch will carry over to the user's behavior in the VE. Hence it is unavoidable to integrate solutions for haptics in VR systems that allow users to behave naturally as they would in reality.

With this in mind, haptics can be treated as an additional dimension which is to be included alongside graphics and sound to form so called multimodal VR systems [3]. The authors of *"Haptics in Virtual Environments: Taxonomy, Research Status, And Challenges"* also state, that the ability to *"touch, feel and manipulate objects in an environment, in addition to seeing (and hearing) them, provides a sense of immersion [...] that is otherwise not possible"* [3]. Moreover they note that it is quite likely, that the addition of even simple haptic interfaces to visual and auditory VR systems, will allow for improvements concerning user immersion that are not achievable by just improving the visual or auditory quality alone.

The Human Sensorimotor Loop

The human sensorimotor loop [3] makes the relation between touch sensation and human motor function apparent. As the human skin touches something, contact forces apply in the region of contact on the human skin. The biological sensors in the skin sense the contact forces and transport this information through the human nervous system to the brain. The brain then processes the information and sends out motor commands to the human muscular system. These muscle commands then cause body motion which in turn triggers new sensor input again. The loop is illustrated in the left half of Figure 2.4.

Tactile Perception vs. Kinesthetic Perception

The human haptic perception is based on two kinds of touch information: *tactile* perception and *kinesthetic* (or proprioceptive) perception. Tactile information refers to the skin's local contact with a surface and entails fine surface information about e.g. the local texture, its smoothness, temperature and friction or the local geometry underneath the skin. Kinesthetic information, on the other hand, entails the more coarse information such as forces applied to the body and the weight and inertia of the touched object. As the sensation of such large-scale force information is coupled with the sensation of the position, orientation

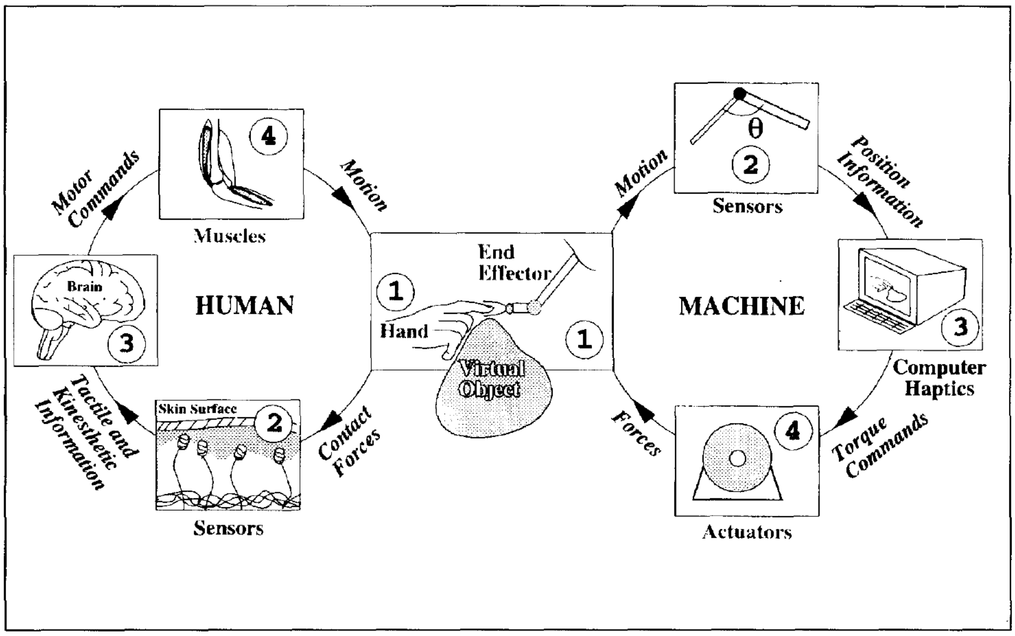

Figure 2.4: The Human and Machine Sensorimotor Loop [3]

and movement of limbs, called proprioceptive perception, both expressions (kinesthetic and proprioceptive sensation) are frequently used interchangeably in the context of haptic perception.

Active Haptics vs. Passive Haptics and Groundedness

Multimodal VR systems that employ haptic technology aim to convey tactile and kinesthetic information to the user. As already mentioned, haptic technology can be classified as *active haptics*, *passive haptics* or *hybrids* combining both active and passive concepts. The following subsection will review the concept of active haptics in some detail. Various examples will be presented and the requirements and the challenges of active haptics will be described. With regard to the introduction of tactile and kinesthetic feedback, it seems noteworthy that up to now, most active haptic devices are designed to either provide realistic tactile or kinesthetic stimuli, with kinesthetic devices making up the majority. Subsequently, the concept of passive haptics will be reviewed and the current state of research on proxy properties will be summarized. Hybrid concepts that combine active and passive haptic approaches are reviewed at the end of the subsection.

Besides the classification in active and passive haptics, a classification on the basis of the groundedness of haptic devices is common. While hybrids exist, devices can typically be classified as either *grounded*, *body-based* or *ungrounded*.

Grounded devices require to have a connection to the ground, typically to be able to actively apply forces to the user. A common example is a force-feedback joystick. Body-based devices do not need a connection to the ground directly, but they need to be mounted on the user's body in order to work. A good example for body-based haptic devices are haptic exoskeletons. Ungrounded devices, on the contrary, do not need to have any connection to the ground, nor do they need to be mounted on the user's body. A good example for an ungrounded active haptic feedback device is the TorqueBAR [27], a handheld device that actively translates a weight to produce feedback.
Besides their differences, all haptic devices have some requirements in common. As the devices all aim to haptically stimulate humans, the limits for all devices are naturally set by the limits of the human perceptual system. Additionally, a crucial requirement for a VR haptic system is, that it should ergonomically be comfortable to use.

2.3.2 Active Haptics

Concept

Active haptic devices are devices that stimulate the user's haptic senses actively by means of computer controlled actuators. For this, they exert forces in order to simulate the haptic sensation of touching a virtual object.
Similar to the human sensorimotor loop is the general feedback-control cycle inherent to active haptics. It is depict on the right side of Figure 2.4. In the machine sensorimotor loop [3], the so called end-effector, the part that the user actually interacts with, measures its state through sensors. The measured data contain information about the end-effector's motion and position and are sent to the main processing computer. The computer runs the computer haptics rendering and controller software. This software processes the measured data and applies computer haptics algorithms to determine the commands that are subsequently sent to the actuators. These commands activate the physical actuators like e.g. servo-motors or heating-pads and let them move in order to exert forces on the user with the end-effector. These stimuli are subsequently felt by the user touching the end-effector and at this point, the haptic information carries over to the human sensorimotor loop. Ultimately, the user's motion-reaction will again be sensed by the end-effector and the feedback-control loop continues.

There is a strong relationship between the algorithms employed in active *Computer Haptics* (CH) and *Computer Graphics* (CG). The haptic rendering algorithms, that render 3D objects haptically to the user, commonly also use surface-based representations of the scene geometry or volumetric models. When the end-effector's position (also called *Haptic Interface Point* (HIP)) is updated during the interaction, the core rendering algorithm uses collision detection methods to check if the HIP is inside an object in the scene and to subsequently compute

the HIP's penetration depth. For this computation, similar to computer graphics, ray- and point-based approaches exist. Accessing the material database, which contains object rigidity, friction and stiffness information, the mechanistic model eventually calculates the force vectors to be applied as a result of the haptic rendering algorithm.
Not all haptic effects can be rendered with such basic rendering algorithms and more realistic haptic sensations require more sophisticated rendering algorithms to be involved. Srinivasan and Basdogan report on some existing algorithms in some more detail [3]. There is a broad variety of algorithms, some of which rely on voxel representations including information about density or viscosity and others aim to include effects like friction.
To enrich the haptic sensations, many shading tricks used in CG are used in CH rendering as well. Some examples are the modification of surface normals through interpolation (surface smoothing) or displacement mapping (adding surface bumps and roughness).
As an equivalent to visual textures, CH introduces haptic textures. These can be categorized, as in CG, into image-based haptic textures and procedurally generated haptic textures. An image-based haptic texture can use a visual texture's gray scale intensities as height information and the height map's local gradients to compute the force direction vectors. Procedurally generated haptic textures use mathematical functions to synthetically generate haptic textures on the fly. Here, as opposed to image-based textures, a *Two-Dimensional* (2D) image lookup is typically not necessary as the gradient vectors and heights can be computed on the fly during rendering.

Besides some algorithmic approaches, haptic rendering algorithms share another very important requirement with their visual relatives: high update rates. But while visual update rates above 150Hz typically suffice by far for human observers to convey fluent motion, such update rates are likely to be too slow for some haptic simulations. This becomes apparent when realizing that the human tactile system has a bandwidth of around 1000Hz. While probably not all features of a computer haptics system need to have an update rate of 1000Hz, still a reactive and very high update rate will be required to deliver believable and realistic effects. In order to reach such rates, advanced acceleration algorithms known from CG can be used, such as e.g. space partitioning acceleration structures and search algorithms.

Hence to eventually reach the goal of a compelling, realistic and believable haptic experience by means of active haptics, sophisticated physical simulations involving *"collision detection, force and tactile feedback computation, surface deformation, hard contact modeling and others"* [2] are to be mastered.

Examples

Burdea [2] and Bar-Cohen et al. [6] summarized some of the most influential and important active haptic devices.
On the one side are the devices that aim to deliver force (or kinesthetic) feedback. Among them are early systems that integrated force-feedback technology in form of an electromechanical arm in robotic tele-operation systems for nuclear environments [28] and systems to haptically render molecular docking [29]. Later, active haptic glove-based systems that were lighter and more portable came up, such as the *Rutgers Master II - New Design* glove [15,30] or the *CyberGrasp*®.

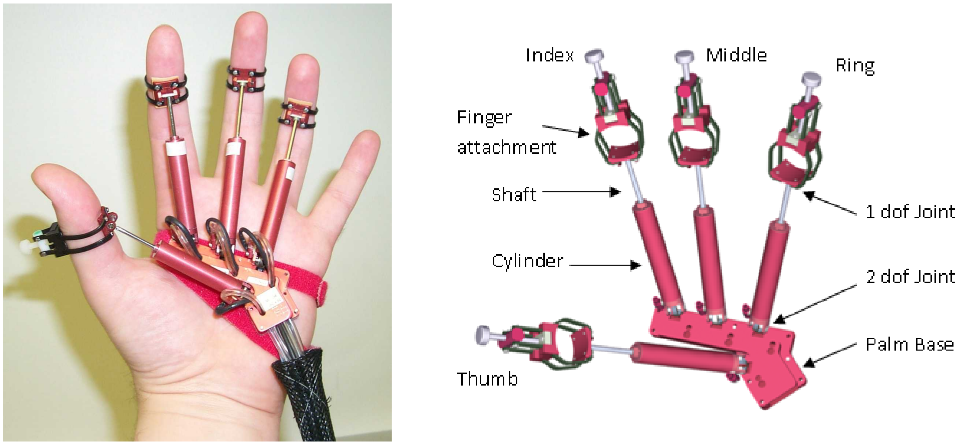

Figure 2.5: General appearance of a *Rutgers Master II - New Design* haptic interface prototype (left) and corresponding CAD model with sensors and actuators (right) © Rutgers University - Reprinted by permission. [31]

Prominent grounded force feedback devices are the *PHANTOM* [32–34] which allows a user to interact with an actuator-controlled stylus end-effector and the *Active Environment Display* (AED), a robot that positions and orients a *Shape Approximation Device* (SAD) in a way, that the user's finger touches it and receives appropriate haptic feedback. A further example is the *Impulse Engine*™ by *Immersion Corporation* which could even be used as a simulation device for laparoscopic surgical procedures [35]. Modern haptic devices are commercially available from companies like *Force Dimension* (*Force Dimension Sigma* and *Force Dimension Omega*) or *Moog Inc.* (*Moog HapticMaster* [36]).

Besides that, a variety of force feedback joysticks designed for the use in games are widely available since the late 90s [37]. Originating from simulator applications, they actively apply forces to the input device to provide a more realistic feeling when steering aircrafts or cars ingame. In addition, gaming consoles use vibration motors in their handheld controllers to provide some haptic feedback. While these controllers do not realistically simulate forces, they do provide cues on what is happening ingame. As the fidelity of their vibration-feedback is limited however, they may be categorized either as force-feedback or tactile feedback.

Figure 2.6: Picture of the *Microsoft Sidewinder Force Feedback Pro* joystick (left; [38]) and the *Logitech Driving Force GT* force-feedback racing wheel (right; [39] - Reprinted by permission)

The company *Tactical Haptics* recently demonstrated a prototype system based on their concept named *Reactive Grip*^{TM} that uses ungrounded tactile feedback to emulate a sensation of force feedback. It *"works by mimicking the friction forces experienced by users"* [41]. The device's handle consist of actuated sliding plates. These plates are computer-controlled and slide up or down to *"induce in-hand shear forces and skin stretch that mimic the friction and shear forces experienced when holding the handle of a device, tool, or other equipment"* [41]. With the *Reactive Grip*^{TM} skin stretch feedback, forces up and down the handle can be emulated when the plates move up or down simultaneously. Additionally, torque is emulated by shifting plates in opposite directions.

Figure 2.7: Picture of a *Reactive Grip*^{TM} controller - Reprinted by permission [40]

Apart from that, recent research demonstrated the potential of enhancing handheld controllers with real reactive force-feedback produced by spinning masses [42]. For that, the introduced handheld prototype exploits the reactive gyroscopic feedback that results when masses in the device rotate at various speeds. A concept that could potentially be used in VR applications as well.
In the context of this thesis, the *TorqueBAR* is worth mentioning here as well. The *TorqueBAR* is a device held in both hands, able to linearly displace a mass from left to right and vice versa along the object. It has been introduced by Swindells et. al. [27]. Although not directly related to haptics in VRs, the *TorqueBAR*, as a device for dynamic ungrounded kinesthetic feedback, turned out to be very inspiring for the experiments on the weight distribution's influence on proxy interaction. The device is able to modify its CM location during runtime, controlled

by a computer. It provides a compelling feedback, as their results suggest, and in conjunction with some research results on human perception introduced in the last section of this chapter, it inspired the design of the second experiment of this thesis.

Besides kinesthetic feedback, devices that aim to provide tactile feedback in VR were developed as well. They frequently rely on vibrotactile stimulation of the skin implemented by small vibrators. These vibrators are commonly embedded in exoskeletons, gloves or grounded devices like joysticks or mice. Examples for active haptic devices simulating tactile stimuli are the *CyberTouch®* glove [20] and the *Sandpaper* tactile joystick [43] that allows users to feel 2D textures [44]. Moreover, Ziat et al. [19] have presented a device that simulated the feeling of an insect crawling on or beneath the skin. As potential applications, the authors note VR movies and games.

Research Results

The review of existing research results concerning active haptics shows, that active haptics can be used in VR applications and games to increase the realism, the immersion and the entertainment factor [5, 19, 33].
When used in VR training applications e.g. for military or emergency personnel, it was shown that active haptics can make users learn an environment faster. Moreover active haptics can decrease the amount of procedural errors while increasing the speed of performance for some tasks [5]. Additionally, it was confirmed that the human brain mixes different kinds of stimuli during perception. When several stimuli disagree, i.e. in the case of an perceptual mismatch, the human brain weights different inputs differently. In many cases, the visual input is weighted very high. This can in turn influence the perception significantly as shown in the paper on force direction discrimination by Barbagli et al. [34]. This effect is commonly called visual dominance.

Discussion

Active haptics offer exciting possibilities as they promise to solve the problems of haptic force feedback and tactile feedback in a very general manner. Nonetheless, many currently available devices come with unavoidable drawbacks. Successful devices need to be *"powerful, yet light and non-obstructive"* [2]. Some of those requirements could already be fulfilled by various devices. But among the most important shortcomings of available devices is their complexity [7]. Most devices, gloves or exoskeletons are inherently complex in design and control. They require sophisticated algorithms in order to work in a way that conveys realistic experiences. Moreover they commonly restrict the user in his movement as they are grounded or body-based and they are expensive [13]. Additionally, the interaction with many active haptic devices is non-intuitive, especially for novice users, and may involve too much levels of abstraction [20].

2.3.3 Passive Haptics

Concept

As opposed to active haptics, the concept of passive haptics does not involve any computer controlled actuators to provide haptic (kinesthetic or tactile) feedback. In passive haptics, haptic feedback is added to the VE by real physical objects that can be touched by the user. These objects are typically low-fidelity physical props (also called proxy objects or proxies) that are registered to a virtual counterpart [7,11] . These props or proxies physically represent the virtual twin-object and provide tangibility [20]. During the VR experience, the user can interact with virtual objects in a natural way by interacting with the physical proxies. The proxies are typically tracked by some suitable tracking mechanism and their motion and rotation is fed into the VR application.

Proxy objects have inherent physical properties that define their shape, size, weight, weight distribution, texture, temperature etc. Besides the influence of their properties on user behavior and perception, an important aspect is the degree of mismatch between the high-fidelity virtual object and the typically low-fidelity physical proxy object that represents it. As already introduced in the section about **Substitutional Reality**, Simeone et al. presented a classification of the mismatch. Their layered model differentiates between 5 classes: replica, aesthetic, addition/subtraction, function and category that approximately represent increasing mismatch [9]. Of course, building 1-to-1 replica objects for each virtual object is not desirable. Thus the goal is to come up with ideas that help to design general proxies. In the optimal case, a single proxy object could then represent n different virtual objects with optimal believability. That is, in a way that users do not perceive any discrepancy.

Examples

There exist many examples of passive haptics being used in VR research. Among them is the work by Insko [11]. He investigated how the augmentation of VEs with static low-fidelity models registered to architectural features like walls, edges and furniture enhances user immersion and spatial learning. He built a passive haptics kitchen environment using cheap materials such as styrofoam and plywood. Figure 2.8 shows how his passive haptics environment looked like. The potential of passive haptics to enhance design, training and simulation applications has been investigated as well, with promising results [7,20,25]. Simeone et al.'s introduced SR concept also heavily builds on the passive haptics idea [9]. The influence of passive haptics on usability and *User Interface*s (UIs) was also covered by some researchers. Lindeman [18] investigated the augmentation of 2D interfaces in 3D VEs with passive haptics. Teather and Stuerzlinger [14] looked at the influence on target pointing performance in 3D UIs.

Figure 2.8: Real and virtual view of Insko's passive haptics kitchen [11]

Besides that, some research addressed the symbiosis of a very interesting field of VR research, namely locomotion in large VEs, with passive haptics [13, 45]. Experiments were conducted, in which recent redirection techniques are combined with environments augmented by passive haptics. Redirection techniques allow users to explore large VEs on foot in a spatially limited tracking area, by imperceptibly injecting small displacements in their visual display. With this, they can make users turn without them noticing it. This allows the computer to steer users to walk in circles or around obstacles while they think they are walking straight, as implied to them by the visual display. The combination with passive haptics can be used to provide tangible experiences for obstacles in such VEs. Users can engage haptically augmented objects, the redirection algorithms then let the user evade all physical obstacles on their way to the target and eventually let the user arrive at a proxy in a suitable end-pose. This allows the user to walk to a virtual object and to interact with it.

In addition to the already mentioned research on passive haptics, an interesting concept introduced by Kohli [46] makes use of the phenomenon of visual dominance. The aim of the introduced technique called *"haptic distortion"* is to generalize proxy objects so that a single proxy object becomes suitable to represent many virtual objects. The core idea here is, to visually distort the virtual object's surface so that it looks like a differently shaped (e.g. curved) surface. Additionally, the space around the virtual object is visually distorted to allow the hand to touch the object simultaneously in real and virtual space. Given the influence of visual dominance and the effect that sensor stimuli are mixed by the brain for perception, this technique has the ability to perceptually simulate many objects with a single proxy.

A noticeable amount of research effort also went into the investigation of different proxy properties and the effects of mismatches between the proxy and the virtual object with regard to those properties. The influence on the user's behavior during the interaction and the user's perception of the haptically augmented objects is of special interest. So far, researchers investigated the following proxy properties:

- Shape (Form, Sharpness of Edges) [9, 21–23]
- Size [9, 23]
- Weight [9]
- Material (Texture) [9, 22]
- Temperature [9, 19]
- Function [9]

The results of these investigations are summarized in the following.

Research Results

Insko's doctoral thesis presents some important results about the influence of passive haptics in VEs. He states that the augmentation of a VE with passive haptics increases presence significantly and it increases spatial knowledge transfer. In his stress-inducing experiment where people faced a virtual cliff, the augmentation of the cliff's edge with low-fidelity passive haptics significantly increased the reported behavioral presence, the participants' skin conductivity and their heart rate [11].

The investigations concerning the use of passive haptics in design, training and simulation applications showed that actually holding something during the interaction was more comfortable and familiar than holding nothing and just feeling vibrotactile feedback. Moreover, it was noted that passive haptics effortlessly allow to grasp a part in any way the user wants. The user can even switch gripping positions at runtime [20]. In the research about augmenting manufacturing studies with passive haptics, an additional important result came up: increasing the fidelity of just a single proxy property does not guarantee better performance nor a higher perceived degree of realism. In some cases, it can make the perception even worse [7]. As an example, one can imagine the situation studied in [7]: The user of an interactive VR application should take a large and heavy part and lift it into a car trunk. The part and the trunk are hereby represented by passive haptic props. If now the large part is represented by a tiny box-shaped proxy, a realistic simulation of the object's weight (a very heavy but tiny box) will be perceived even more unrealistic, than a less realistic light and tiny box. But when the proxy object's size and form is closer to the real part's shape (a large box), a realistically heavy proxy will increase the perceived realism compared to a very light and large proxy. In general however, using movable and static passive haptic props does improve the results and the performance of manual assembly process simulations [7]. Similarly, the investigation of UI pointing performance showed, that passive haptics can improve it and subsequently can improve the usability of VEs [14]. Moreover, registering physical proxies with virtual interactive UI surfaces can improve general user performance and presence [18]. As found by Hoffman, the interaction with passive haptic proxy objects can influence the perception of other objects in the VE [12]. If the first object a person interacts with provides tangible feedback, the experience might influence the user's perception of other objects' properties even if the user never interacts with them. Through the first tangible experience, the user learns about the physicality in the VE and deduces how other objects in the VE might feel like.

Concerning research on individual proxy properties, the most frequently considered aspect is a proxy object's shape or form. Nakahara et al. investigated how the sharpness of a proxy object's edge is perceived when visually a CG edge is overlaid [21]. In the experiment, the visual sharpness could differ from the real sharpness and the investigation focused on how sensor stimuli interact with each other. Their results confirmed the important role of the visual perception. The *"haptic stimulus seems to be affected by visual stimulus when a discrepancy exists"* [21]. An edge overlaid with a duller CG edge was perceived duller by the users. Hence the perceived sharpness of edges can be controlled to some degree by overlaying duller or sharper CG edges.
Kwon et al. investigated the influence of a shape and size discrepancy on interaction usability, object presence and object manipulation performance [23]. In general, the obtained performance and the perceived realism was best when size and shape of the proxy matched the virtual object's. Mismatches in size did not significantly decrease the object manipulation performance while mismatches in shape did. The authors conclude as a result that it is more important for a proxy to correctly model the shape of a virtual object than its size.
Besides the proxy's shape, Kitahara et al. also investigated the texture of a proxy object and the influence of visual-haptic discrepancies [22]. Their investigation on the shape property again concentrated on the perceived sharpness of an object's edge when overlaid with CG edges. The results are equivalent to the results already mentioned. The results on texture perception additionally revealed that the perception of material or texture can be controlled by exploiting a visual-haptic discrepancy as well. As an example, a user learned in the past that a material A can have different haptic properties resulting in different impressions (e.g. A can be rough or smooth). Then, the haptic perception of a smooth material B in conjunction with the visual perception of material A can increase the user's believe that he faces a smooth material A. Moreover, displaying a smooth material A while touching a rather rough material A can make the user think he also touches a smooth version of the material A. The human perception uses information from the past to check the mixture of haptic and visual impression for plausibility, using e.g. the knowledge of possible haptic impressions of a certain material.

Thus by exploiting past experiences with materials, the perception of a proxy's texture or material may be controlled to some degree by the visually overlaid virtual texture or by using materials with similar haptic properties. Although the brain mixes the visual and haptic input during perception, the haptic sensation seems to play a more important role in texture perception than the visual input. In Ziat et al.'s recent paper investigating the perception of temperature and the influence of the proxy's color on temperature perception [19], however, the influence of the visual input plays an important role. The perceived temperature of a physically warm mug was rated higher when the virtual mug was displayed red and lower when it was rendered blue. The same effect was observed for a physically cold mug. The virtual mug was perceived colder when rendered in blue and less cold when rendered red. Thus the visual input seems to influence the user's perception of a proxy's temperature and allows it to be controlled to some degree by the proxy's color.
The most extensive investigation of proxy object properties so far was conducted by Simeone et al. [9]. Overall they studied the influence of the shape, size, temperature, material and absolute weight on the perceived realism, immersion and the ease of use. Moreover, their second user study investigated the influence of the functional aspect. The aim of this study was to investigate, whether a proxy object whose function differs from that of the virtual object can yield similar engagement and immersion as exact replications. They found that if no exact replications are available, those proxies with similar properties in the parts most likely interacted with, suit best for substitution. They further report that real-virtual pairings with greater variations in the shape, material, temperature and weight had the most impact on believability. Moderate mismatches in shape however did not affect the believability much. But in summary it holds for all proxy properties they investigated, that the more extreme the real-virtual mismatch becomes, the more this discrepancy negatively influences immersion. Additionally, the result on the functional difference revealed a very interesting point: A functional difference does not have to negatively influence the experience. Their experiment showed that functionally different proxy objects can engage users as much as exact replicas. In gaming-scenarios, especially when fantasy objects not known from reality are involved, a functionally different object might even be favored by users as it might be more comfortable to handle and might weigh less than a correct replica. In addition to that, the user also lacks real world experience with the fantasy object and might thus be more absorbed in the idea to really interact with it. But this aspect does not only influence the proxy objects, it might influence the whole VE. VEs with realistic settings might have stricter presence requirements than fantasy-based VEs as the user has more real world experience with realistic scenarios and might thus be more critical.

A summary of the most important research results on proxy properties can be found in Table 2.1.

Proxy Properties - State of Research

Property	Results	Reference
Shape	• mismatch can sensibly affect believability and immersion	[9]
	• object manipulation performance best when matching	[23]
	• perceived realism highest when matching	[23]
	• mismatches have a significant influence on object manipulation performance	[23]
	• visual stimulus affects haptically perceived edge sharpness	[21,22]
Size	• mismatch can affect believability and immersion	[9]
	• object manipulation performance best when matching	[23]
	• perceived realism highest when matching	[23]
	• mismatches do no significantly decrease object manipulation performance	[23]
Weight	• mismatch can sensibly affect believability and immersion	[9]
	• less realistic simulation may increase usability and fun (especially in games, especially with regard to fantasy objects)	[9]
Material	• mismatch can sensibly affect believability and immersion	[9]
	• can affect expectations on physical properties of the proxy	[9]
	• perception depends much on past experience with displayed material (knowledge of the material's different haptic impressions)	[22]
	• by exploiting past experiences with a material, the perception can be controlled to some degree by using materials with similar properties or by overlaying different virtual textures	[22]
	• haptic stimulus affects the texture impression more strongly than the visual stimulus	[22]
Temperature	• mismatch can sensibly affect believability and immersion	[9]
	• perception can be controlled to some degree by the color	[19]
	• red color ~ warmer	[19]
	• blue color ~ colder	[19]
Function	• difference does not have to negatively influence immersion	[9]
	• different objects may engage users as much as replicas	[9]

Table 2.1: Table summarizing the state of research on proxy properties

Discussion

The concept of passive haptics comes with many advantages compared to active haptics but involves new challenges as well. The effect of the mismatch in various dimensions has been investigated as summarized above but the knowledge-base is not complete yet. For the design and development of immersive VR experiences that provide tangibility through passive haptics, it is crucial to know which proxy objects are suitable to represent which virtual objects. To assist these development processes, the influence of as much proxy properties as possible should be investigated so as to preferably derive a set of proxy-design guidelines. Many of the complexities involved in active haptics technology however are not involved in passive haptic approaches, which is a major advantage. It is not necessary to simulate and compute all the physical quantities like forces, friction, inertia etc. Consequently, it is not necessary to run haptic rendering engines that keep update rates of almost 1000Hz. Instead, a thorough design process that comes up with suitable real-virtual pairings or proxy-object recommendations suffices. The kinesthetic and tactile feedback is provided by the physical props themselves then and since the user directly interacts with a physical object, it is one level of abstraction closer to reality than pure virtual-virtual haptic scenarios using only gloves [20].

As the influence of the proxy *weight distribution* and the corresponding mismatches on VR user behavior and perception is not yet studied, this thesis aims to fill this gap. The results of this thesis will join the ranks of the results summarized above. In other words, it will add an additional row for *weight distribution* to Table 2.1 to further complete the knowledge-base on proxy object properties.

2.3.4 Hybrids

Concept

Some haptic interfaces are not easily classifiable as pure active or pure passive haptics. Instead, some concepts and devices exist that employ features both attributed to active haptics and passive haptics respectively.
A typical example would be a physical proxy object augmented with some computer controlled actuators. The physical properties like forces, inertia and texture feel would then be provided by the proxy object itself. Just as with passive haptics, it would not be necessary to simulate and compute the physicality nor to actively simulate each and every force or tactile feature with actuators. Instead, active computer controlled actuators are used just to modify the properties of the object slightly during runtime to make the proxy more general. A computer controlled heating-mechanism could for example change the proxy’s temperature, pneumatic actuators could alter the proxy’s tactile feedback or vibrators placed on the proxy could provide additional information about collisions with virtual objects.

As a result of the combination, hybrid haptic interfaces share, depending on their specific design, qualities and challenges with corresponding passive and active haptic concepts.

Examples

One example of a hybrid haptics device is the haptic *Airbat* game controller introduced by Faust et al. [17]. They investigated haptic feedback in pervasive games that mix real and virtual content. The graspable *Airbat* controller represents the paddle in their breakout-style game *Airkanoid*. The bat itself can be seen as a proxy object. It is augmented with vibrators controlled by the game. These vibration-actuators produce feedback when a virtual ball was hit and due to this combination, the bat can be classified as a hybrid haptics device.
An additional example is Borst et al.'s approach which combines passive haptics (a real physical panel as proxy) with an active haptics force-feedback glove. The combination here is used to improve the interaction with a virtual control panel [15].
Clark et al.'s [20] initial goal was to study a system for 3D engineering and visualization that uses active haptic feedback to enhance interaction. Virtual parts should be grasped, oriented and patched together using a vibrating glove. But soon, the authors reported on several problems related to the usage of only active haptics. Users reported to get lost in 3D and that important haptic (kinesthetic and tactile) cues were missing which impaired interaction. The authors summarize the problem by stating that an all-virtual approach was *"too far from reality"* [20] as it involved too many layers of abstraction. Their solution was to lift the interaction from a virtual-virtual stage (where the interactive object is virtual and all other objects are virtual as well) to a virtual-real stage (where the interactive object is real and only all other objects are virtual). The implementation of their solution used a real physical proxy in conjunction with active vibration feedback.
An experiment conducted by Ziat et al. [19] showed another way to design hybrid systems. The virtual cups in their experiment were registered spatially to real cups. Using a thermo-electric cooler and an electric heating pad, the real cups could be cooled and heated. In this scenario, the cups represented tangible proxies which were augmented by actuators controlling the proxy's temperature [19].
Finally another example for possible hybrid haptic designs is the *Linked-Stick* [47]. The servo-motor powered shape-changing stick is not introduced as a VR proxy object explicitly, but proxies based on the *Linked-Stick*'s design could be imagined. The stick itself would then provide kinesthetic and tactile feedback during the interaction and thus would serve as a proxy. Through computer controlled shape-shifting, it could alter some of its properties such as its form, size or even its CM location. Additional ideas for actuation mentioned by the authors even include changes in texture or thickness.

Figure 2.9: Picture of the *Linked-Stick* [47]

Research Results

It was reported by Faust et al. that their hybrid haptics device *Airbat*, augmenting a proxy with vibration feedback, provided a greater sense of immersion [17]. Borst et al.'s investigation of a hybrid haptics approach to virtual control panel interaction showed, that a hybrid approach can result in significantly better performance and user popularity compared to a pure active haptics approach [15]. The users also preferred the mixed approach over the pure passive approach. However, the authors did not obtain significantly better performance in the interaction with the control panel using the mixed approach compared to a pure passive haptics approach. In conclusion their results show that the augmentation of passive haptics with some active haptic features can improve performance and usability. Moreover they note, that haptics in general *"enhance interactions performed outside the field of view"* [15].
The adjustment in Clark et al.'s paper was to use a physical proxy as interaction object in addition to an active haptic feedback glove [20]. By this, they effectively removed one layer of abstraction. The result was, that most of the problems reported in the pure active haptics approach vanished. Users could interact much more naturally as the proxy could be grasped in arbitrary ways and delivered real tactile and inertial feedback. Collision forces were still conveyed with the vibration glove or by vibrators inside the proxy. This effect nicely completed the impression. Thus the integration of hybrid haptics improved the overall usability of their system crucially [20].

Discussion

In conclusion, hybrid haptics approaches are very promising as they combine the most important advantages of passive and active haptics. At the same time, they overcome many drawbacks through their combination.
One of the most important challenges for passive haptics is the generality. In some applications, it may be very difficult to design pure passive haptic proxy objects that believably represent many virtual counterparts. On the other hand, it is of course not desirable to have a distinct proxy for every object the user can interact with. Beside these drawbacks, passive haptic proxies come with many tangible features that can only hardly or not at all be simulated realistically with active haptics. Other drawbacks inherent to active haptics, such as the spatial limitation, are undesirable as well. But the variety of available actuators offering great generality is an important advantage of active approaches.
As a result, it can be concluded that the combination of passive haptic proxies, with all their tangibility and physicality, and active haptic actuators, with their generality and adaptability, is a promising mix with an enormous potential to shape future VR interaction.

2.3.5 Wrap-Up

This section introduced research on active, passive and hybrid haptics. It is supposed to give a general overview of the field of haptics research and the methodologies used for investigating effects on immersion, perception and interaction in VR. The examples demonstrate the diversity of haptic technologies and the presented findings of the related research emphasize the great potential of haptic feedback in VR. Active haptics were introduced as they promise a general solution to the problem of haptic feedback by CH. But besides the benefits, the presented examples also demonstrated the drawbacks of this approach like mechanical and computational complexity. Passive haptics promise to solve the problem of complexity while still providing compelling and realistic feedback. However, passive haptics approaches were found to be less flexible. The examples of mixed devices eventually showed how the advantages of active and passive approaches can be combined to remove their limitations.
This thesis introduces an investigation of an understudied proxy property that is in line with the methodologies of the presented related research on passive and active haptics. It fills a gap in past research on proxy interaction and eventually provides design recommendations for passive proxies and hybrid devices.

2.4 Immersion

2.4.1 What is Immersion?

The term *immersion* is frequently mentioned in the same breath with the term *presence* in VR literature. In fact, depending on which definition of immersion or presence is considered, the difference between immersion and presence can be so small that both terms are frequently used as synonyms. However, subtle differences exist as immersion is a more *"technology-related"* term while presence is considered the *"psychological, perceptual and cognitive consequence of immersion"* [48]. The origin of two different names describing almost the same or similar phenomenons is due to the areas those terms are commonly used in or come from. While presence is a term originating from the area of teleoperation, immersion is commonly used in areas like games or movies [49].

There exist various conceptions of what immersion is, but an exact definition is hard to formulate. Among the most recognized definitions of immersion is the one by Murray: Murray describes immersion as *"the experience of being transported to an elaborately simulated place"*. He details that immersion is *"the sensation of being surrounded by a completely other reality, [...] that takes over all of our attention, our whole perceptual apparatus"* [50]. Lombard and Ditton analyzed several definitions and concepts of presence and they identified a *"central idea"* shared by all conceptualizations that is very close to Murray's definition of immersion [51]: Presence means *"the perceptual illusion of nonmediation"* [51]. In other words, when immersed, the user behaves as if the perceived world would not be mediated by human-made technology but instead as if he would really be inside the virtual environment. The user *"fails to perceive or acknowledge the existence of a medium in his/her communication environment and responds as he/she would if the medium were not there"* [51].
In the context of VR systems, this can be interpreted as a mental and physical state in which the user is not directly aware of the VR system. Instead, the VE has taken over most (if not all) of his attention. As a consequence, the user unconsciously behaves as if he would really be present in the computer generated world and not as if he would control a computer [52]. When being immersed, there is no longer a border between the user and the virtual world with its virtual objects because the technology behind the illusion becomes perceptually invisible [51].

As immersion (and presence) is a perceptual phenomenon, immersion is not a property of the system but instead a property of the user. It is something individual and dynamic that is different across users and also time-varying for each individual user [51]. A user's degree of immersion changes as he interacts with the VR system. In some moments in time he may be more immersed than in others. Research on immersion in games showed that once a certain degree of immersion is established, it can make the user fail to notice usability issues and behavioral discrepancies [53].

2.4.2 Influential Factors and Layers of Immersion

As immersion originates from the interaction of the user with the VR system, the VR system is not solely responsible for the experienced immersion. It is rather a property of the user. But some aspects of the VR system can facilitate immersion while others can be obstructive.

VR systems aim to be media that foster long-lasting and strong immersion. Concerning the audiovisual dimension in VR systems, the usage of e.g. VR-HMDs and headphones blends out the stimuli of reality and substitutes it with stimuli of the VE. By this, some factors that may inhibit immersion are effectively removed which, in principle, opens the way to greater degrees of immersion. But it is important to note, that this is not a necessity for immersion to ensue. Immersion occurs also during desktop gameplay at a PC with a normally sized computer monitor that does not completely blend out the surrounding [52].
The audiovisual implementation is presumably an important factor influencing immersion but certainly not the only one nor the most important. While quality improvements in all three modalities (visual, auditory and haptic) of multimodal VRs does influence immersion, structural aspects concerning the virtual world seem to be at least as crucial [49, 52]. McMahan states that for an immersive VR experience,

- the conventions of the VE should match the expectations of the user,
- the user should be able to do non-trivial and meaningful actions that influence the VE and
- the virtual world must be consistent.

These structural factors promote interactivity which is encouraged by challenges and tasks. There even exists evidence, that the difficulty of the challenges in the virtual world can affect immersion [52]. This again emphasizes the importance of taking the step from pure passive VR applications to interactive applications as interactivity unlocks the potential of greater immersivity.

Ermi and Mäyrä developed a gameplay experience model that describes three kinds of immersion that occur during gameplay [52]. These levels of immersion exist in VR and non-VR gameplay. The first level is *sensory immersion*, which describes the immersion coming purely from the sensation of audiovisual and haptic stimuli. The virtuality-based sensations overpower those from reality and thus immerse the player on a sensory level. The second level is *challenge-based immersion* which is the immersion coming from balanced challenges in the world. The user's tasks are demanding but match his abilities and through interaction he enjoys to fulfill and master them. The third level of immersion is the *imaginative immersion* that accrues when the user is absorbed in the stories of the game, uses his imagination and starts to feel for or identify with a game character.

Brown and Cairns introduced another model of immersion which is divided into three levels representing increased immersion [54]. According to the authors, the prerequisite for each of those levels is that the barriers to them (on user-side and system-side) are removed and that all previous levels are already established. Fulfillment of this prerequisite does not, however, guarantee the next highest level of immersion to ensue but rather allows for it. The lowest level in this model is *engagement*, followed by an increased immersion in the level *engrossment*. The ultimate level of immersion is called *total immersion* and refers to the extreme case as defined above by Lombard and Murray. Concerning interaction, Brown and Cairns mention that *"an invisibility of controls"* is a fundamental prerequisite for total immersion to accrue [54].

Regarding the influence of haptics, results described in the previous sections already emphasized that the addition of even simple haptics can facilitate levels of immersion that are not achievable by the enhancement of the audiovisual quality alone [3]. In order to know how important individual haptic features or proxy properties are for immersion, a lot of research has been conducted as already described in the section about **Haptics in Virtual Reality**.

2.4.3 Measurement

Different methodologies exist to measure immersion or presence. One can try to capture the degree of immersion by observing the user's behavior or by monitoring physiological signs [11, 55]. Moreover, a huge body of literature exists on presence measurement questionnaires that try to deduce the degree of immersion from answers and ratings of the user [56].
A common questionnaire used in the related literature is the so called *SUS-Presence-Questionnaire*, named after the authors Slater, Usoh and Steed [9, 55–57]. It aims to map the user's degree of immersion to a number between 0 (not immersed at all) and 6 (totally immersed). It consists of six questions rated on a scale from 1 to 7 and the final score is the amount of high ratings (6 or 7) per person.
The SUS questionnaire primarily considers the *"sense of being there"*, the *"extent to which the VE becomes more 'real or present' than reality"* and the *"extent to which the VE is thought of as a place visited"* [56]. As it is an accepted rating in the related literature, it was used in the experiments of this thesis as well.

2.5 Human Perception

Human perception is a very general term covering all sorts of perceptual channels. This section however is only concerned with work on human perception closely related to the topic of this thesis: the influence of an object's *weight distribution*. It summarizes some results from neuroscience and psychology that provide the basis for the experiments conducted in this thesis.

2.5.1 Influence of Center of Mass Predictability on Grasping

While not concerned with VR or proxy interaction, the investigations of Lukos et al. are closely connected to the first experiment of this thesis [58]. Lukos et al. investigated how humans choose contact points of individual digits as a function of the estimated CM location of the object that is picked up. They found that when a human can predict an object's CM location visually, he will adjust the placement of contact points so as to apply the necessary forces counteracting unwanted movements like e.g. object roll more efficiently and comfortably. On the other hand however, when the CM location is not predictable, a default grasping strategy is applied. For an object that seems to have a symmetric weight distribution, this default grasping strategy is equivalent to the gasping applied when the CM location is predictable at the center location. Their experiment showed that in case the CM location is predictable, the object roll during lift up is significantly smaller than when the CM location is unpredictable. This is due to the fact that in the predictable case, fingertip positions are planned and adjusted before lift up while in the unpredictable case, fingertip positions and contact forces are only adjusted shortly after lift up.
Thus, the results of Lukos et al. give hints on how the proxy's weight distribution might influence interaction in VRs. But as their investigations were only concerned with predictability in reality-based scenarios and not with explicit visual-haptic CM location discrepancies in VEs, further research is conducted in this thesis.

2.5.2 Nonvisible Rod Length and Weight Perception

The second experiment of this thesis focuses on the influence of the proxy's weight shift on the user's perception of the virtual object. Related to this are results from neuroscience and psychology about the perception of nonvisible rod length and weight.
The human perceptual system specifies the haptically perceived length of a rod held in the hand *"by a force structure [...] that produces tissue deformation on muscle and tendon"* [59]. Muscles act here as sentient *"smart instruments"* [60] that are vitally important for the haptic perception process.

"Perceived length is not just a function of actual rod length" [59] as these force structures vary not only with the length of rods but also with other physical quantities. Specifically, researchers found that the perceived length of an occluded rod when wielding it depends on the

- moment of inertia
- density
- CM location
- felt thickness
- known thickness

of the rod.

The main criterion for nonvisible rod length perception is the moment of inertia [59, 60]. The moment of inertia is *"a measure that takes into account both the mass of the object and how that mass is distributed relative to the rotation axis"* [60]. It is *"the resistance to rotational acceleration"* [59] and it significantly affects the force structure sensed by the haptic sensory system at the wrist when wielding. It was also shown that the sensation at the wrist is crucial for length perception and that perceived length is proportional to the moment of inertia [60]. Thus an increase in the rotational resistance increases the perceived length.
Likewise it was shown that, as density can change the moment of inertia as well, it also influences the perceived length of occluded rods. The proportionality was consequently found to be the same as for the moment of inertia: an increase in density results in an increase of perceived length.
Chan additionally showed, that the felt thickness of the rod also affects the length perception. For thick rods, increased wrist stiffness and muscle tension prepare the user to lift a large and heavy object and let the same moment of inertia appear comparably light. Thus felt thickness seems to affect perceived length in an inversely proportional manner.
Similar conclusions were drawn for the known thickness. If a rod is known to be thicker, implied through e.g. the visual feedback, it is perceived shorter.
Highly important for this thesis is the relation of the weight shift to the perceived length of nonvisible rods. The moment of inertia can be influenced by the CM location as well. When wielding a rod-like object held at one end, the rotational axis is close to the wrist. Hence, increasing the distance of the CM location to the rotational axis by translating it away from the wrist inevitably increases the moment of inertia and thus the perceived length. Vice versa, lowering the distance decreases the moment of inertia and likewise the perceived length [60]. All these results are summarized in Table 2.2.

Influential Factor	Increase	Decrease	Reference
Moment of Inertia	Longer	Shorter	[60]
Density	Longer	Shorter	[59]
Distance: CM $\leftrightarrow$ Rotational Axis	Longer	Shorter	[60]
Felt Diameter	Shorter	Longer	[59]
Known Diameter	Shorter	Longer	[59]

Table 2.2: Table summarizing the influence of the most important factors on nonvisible rod length perception

Similar to the perception of nonvisible rod length is the perception of nonvisible rod weight. Turvey found, that also perceived heaviness depends primarily on the moment of inertia felt when wiedling [60]. In his experiments with occluded rods, rods with larger rotational inertia were perceived heavier compared to rods of the same weight with a smaller moment of inertia.

2.5.3 Wrap-Up

These related results provide the basis for the research on proxy object interaction and perception conducted in this thesis. Nevertheless, none of these results is explicitly concerned with VR proxy object interaction. In fact, all of these results originate from reality-based scenarios and they all apply to the case of wielding *nonvisible* rods.
In VR interaction, the situation is somewhat different as the virtual interaction object is permanently perceived visually and the interactions performed with the objects are somewhat more complex than just wielding them. Hence, this thesis will lift the related findings to the VR domain. Besides the main research goals, this thesis also aims to verify some of the related results by investigating the influence of the CM location and corresponding discrepancies on VR object perception and interaction. Additionally, ways to include results from psychology research in the VR domain are introduced, promoted and demonstrated with the conducted experiments.

Chapter 3
Concept

This chapter introduces the general concept of the experimental approach and the implementation of this concept in the course of this thesis.
The **Overview** section reviews the design and development process that took place. It recalls considered concepts for experiments and proxy designs. Subsequently, it introduces the conducted pilot study and summarizes the conclusions drawn from it. At the end, the section briefly introduces the design of the main study.
The section **Implementation** describes this thesis' implementation of these concepts. It summarizes the hardware setup and the software architecture of the VR system and details on the proxy object construction.

3.1 Overview

The existing body of **Related Work** about human perception, VR interaction and the influence of proxy properties thereon makes a research gap concerning proxy weight distribution apparent. This lack of research motivated the thesis to study the effect of proxy weight distribution on user interaction in VEs with passive haptic proxy objects. Inspired by the related work on other proxy properties, an experimental approach seemed to be the optimal way to do this. Thus the first step towards filling this gap was to elaborate a set of experiments suitable for the investigation. From these experimental concepts, a set of requirements for the VR system and the used proxy objects could be derived.

3.1.1 Early Experimental Concepts

In the first iteration of the concept development process, a set of initial experiment concepts was invented. All considered experiments were designed in a way that allowed both novice and expert participants to play small games live in a lab-based VR system. During the experiment, they were instructed and observed by an experimenter. This fundamental concept remained unchanged during the entire development process. The concrete procedure of the experiment however had to be selected from a set of different ideas, some of which are introduced in the following:

One considered concept that crucially influenced the final experiment involved an interactive virtual dumbbell used by the participant to hit targets positioned in his environment. This target-pointing task was designed to measure pointing performance and object manipulation performance. Moreover it was supposed to measure the influence of weight distribution and corresponding visual-haptic discrepancies on subjective ratings of enjoyment, comfort and perceived realism. The virtual interaction object was chosen to be a large dumbbell as its design is suited perfectly to visually convey different weight distributions. Furthermore a dumbbell's kinesthetic impression is familiar to most people. The dumbbell object was supposed to either look balanced or to imply a weight shift to the left or to the right through attached virtual weights. Simultaneously, the real proxy's CM location was supposed to either exactly match the virtual object's or to differ. This difference would then introduce several levels of CM location discrepancy. Regarding the targets in this target-pointing task, 4 targets positioned on the left hand side in front of the user and 4 targets positioned on the right hand side were considered. The idea was to let the targets light up several times in a randomized order and to measure the time the user needs to hit the targets. Following up, the users should state the subjective ratings by answering questions of the experimenter.
After repeating the target-pointing task with every combination of real and virtual weight distribution, a second experiment measuring the influence of discrepancy on interaction accuracy was planned. Here the user was supposed to hit the bullseye of a virtual target as accurate as possible with a peaky virtual ice axe. This ice axe would then be haptically simulated by proxies with different weight distributions in each repetition. The extension of this concept even planned to compare the measures of differently weight-shifted proxies to those of proxies with different absolute weights to investigate which property has greater influence on the measure. However these follow-up experiments on the interaction accuracy were not conducted due to the already long duration of the eventually chosen experiments. While accuracy is without doubt a very important aspect of interaction, in an immersive game setting, it is not the primary concern for the experience. Since not all experiments developed for this thesis could eventually be implemented, other experiments had priority during the selection process. But nonetheless it is highly recommended to investigate this aspect further in future work on this topic.

Besides experimental concepts concerned with interaction performance, findings of Turvey [60] and Chan [59] inspired two additional experiments focusing on the user's perception of virtual objects during VR interaction. These experiments aimed to investigate whether virtual objects of different lengths and weights can believably be simulated by proxies that only shift their CM location to alter their moment of inertia while keeping their weight and length unchanged. Users were supposed to be placed in an immersive game-like VE that allowed for game-like interactions. A concept for a short experiment was invented in which participants were given differently weight-shifted proxies of the same length and absolute weight. Their task was then to select from a set of virtual objects those, which best matched their impression of the real proxy in their hand. The objects to choose from where of different lengths and weights. The goal of the experiment was to evaluate the perception of virtual objects, when visually perceived through the VE and haptically perceived through the real proxy object. The experiment can also be regarded as a proof-of-concept demonstrating that Turvey's and Chan's findings still hold in multimodal VEs and that the effects described by them can be made applicable for VR systems.

The first iteration of the concept development process thus came up with a set of different experimental concepts that were improved and extended in the second iteration. After that, a pilot study was conducted to gain first insights.

3.1.2 Pilot Study

The target-pointing experiment made it through the selection process and an improved version thereof was performed in the course of a pilot study. Here, the experiment put the user in a neutrally looking VE and let him hit targets as described before. In front of the user, 8 small spheres (called *single-targets*) were located in the user's immediate reach and small balls at the right and left end of the virtual dumbbell had to be placed completely inside them in order to charge them for a specific amount of dwell time.

After charging a single-target, the user had to re-position the dumbbell to a default location directly in front of him. This was enforced by a *double-target*. This double-target consisted of 2 spheres and it charged only if the dumbbells' right ball was inside the right sphere and the left ball was inside the left sphere.
These kinds of chargeable targets were chosen to investigate the performance of the user in an exact pointing interaction. Single-targets made the user focus on a single end of the proxy while double-targets forced the user to consider both ends simultaneously, which increased the mental load.
The within-subject design of this pilot-experiment made each of the participants play the game with every real-virtual weight distribution combination. 3 possible virtual distributions (*left, center, right*) and 3 real distributions (*left, center, right*) yielded 9 possible combinations. The proxy was initially placed on a stand in front of the participant and as soon as a countdown was counted to 0, the participant was allowed to lift up the proxy and to play the game on time.

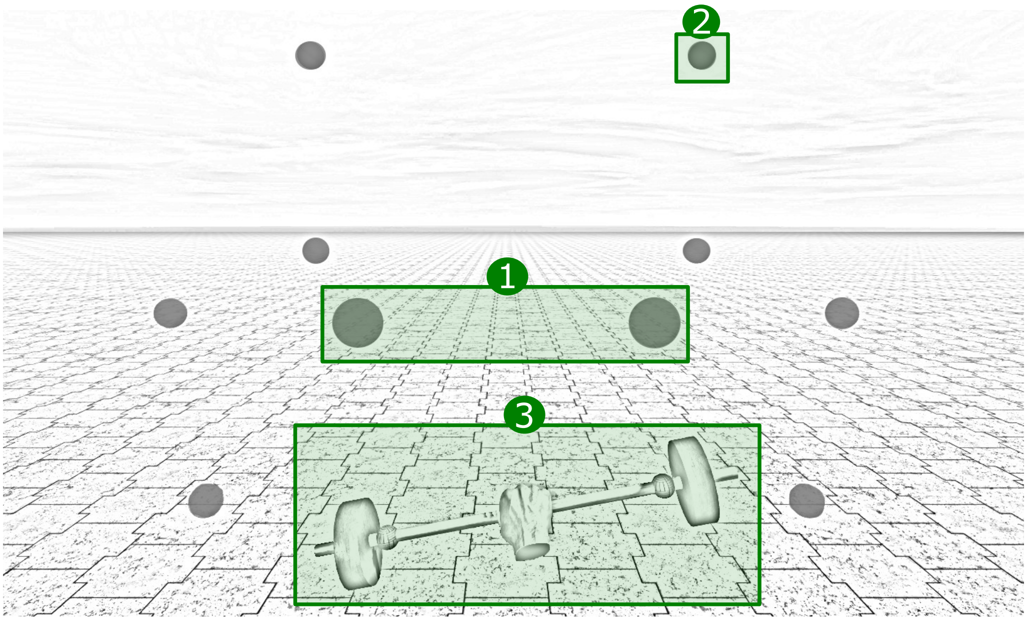

Figure 3.1: Sketch of the double target *(1)*, the single-targets *(2)* and the virtual dumbbell *(3)* with the virtual weights and the two wooden balls in the VE of the **Pilot Study**.

Four participants took part in the pilot-study and the results provided important insights in the interaction with differently balanced proxies. As charging all targets with a single real-virtual configuration took around 2 minutes, the discrepancy could unfortunately not clearly be seen in the total time measured. By observing the participants while playing, it became apparent that the discrepancies in the weight distribution strongly affected the user's behavior early in the interaction but the effects vanished quickly when the user concentrated on the task. The participants typically compensated for mismatches in weight shift during the first minute led by their visual input. This made the effect vanish in the general noise of the comparably long experiment. Consequently only weak or no effects showed up in the statistics comparing the total times of the different configurations. Thus, statistically significant results would require a huge amount of participants which was unfeasible in this lab-based experiment.

Lessons were learned from the pilot study results and the last iteration thus adapted the experimental concepts again to incorporate these early findings.

3.1.3 Main Study

The final concept of the main study consisted of 2 main experiments conducted in succession. Each experiment consisted of 2 subsequent phases.

***Experiment 1: Warm-Up & Lift-Up* (E1)**:

- ***Phase 1: Warm-Up* (P1)**
- ***Phase 2: Lift-Up* (P2)**

***Experiment 2: Length & Weight* (E2)**:

- ***Phase 3: Length* (P3)**
- ***Phase 4: Weight* (P4)**

The first experiment (E1) focused on the influence of proxy weight distribution on user behavior in the initial lift-up interaction.
In its first phase (P1), the original pilot-study experiment was played as a warm-up. This allowed the participants to familiarize with the interaction in the VE and with the feel of the dumbbell object. The users played the target-pointing game on time multiple runs in succession without any mismatch in the object weight distribution: at first with the balanced dumbbell, then with the right-shifted and finally with the left-shifted dumbbell. Post-task questions were asked after each run and upon completion, the second phase was conducted.
In this second phase (P2) the participant's main task was simplified to only lifting up the virtual dumbbell horizontally into a double-target located slightly above his head in front of him. Errors manifested hereby in unwanted angular deviations which were measured for the investigation. The lift up was done multiple times in direct succession for each real-virtual weight distribution combination. While the visual distributions remained unchanged compared to the pilot-study (*left, center, right*), the real distributions changed slightly. To cover more discrepancy levels while not increasing the amount of played combinations, no real left-shift was played. Instead, an additional real right-shift with a CM shifted to the point halfway between center and full right-shift CM was introduced. This weaker right-shift was called half-right-shift. To ensure equal conditions for all participants, being right-handed became a necessary condition for participation in the experiment. Each run was finally concluded by the same post-task questionnaire as in P1.

The second experiment (E2) was designed to focus on the user's perception of virtual objects during the interaction with differently weight-shifted proxies.
Here, the experiments on length and weight perception introduced as **Early Experimental Concepts** were conducted in the third and fourth phase (P3 and P4) respectively. In each of both phases, the participant received several weight-shifted proxy objects in his hand and could then choose among several virtual wooden sticks of different lengths (in P3) and weights (in P4). The goal was to

select the stick that most closely matched their haptic impression. The real proxy objects however never changed in length or weight. Instead, they only differed in their weight distribution. For these final phases, the user was put into a less neutrally looking virtual desert environment. To further increase the game-like feeling, the selection process was made more engaging as the user could interact with virtual cubes hanging at virtual springs in the VE.

3.1.4 Derived Virtual Reality System Requirements

As all phases of the experiments took place in game-like settings, the main requirements for the VR system, being the experimental platform, could be directly derived: the user should be able to stand upright in a VE, the system should provide compelling graphics on a level with modern first-person video games, it should be able to provide auditory feedback and of course, it should allow to interact with objects in the VE by means of passive haptics.

3.1.5 Proxy Concepts

Besides the experiments themselves, the corresponding proxy objects had to be invented. A common feature of the considered experimental concepts was the interaction with a rod-shaped proxy held one-handed horizontally at its center or vertically like a stick, sword, racket or axe at the grip. To show that general VR proxies can be constructed with simple, readily available and cheap materials, several different proxy objects were considered during the design process.

In order to be applicable for the considered VR interaction however, some basic requirements had to be fulfilled by them. The proxy objects should be rod-shaped or dumbbell-shaped and they should offer several different states of weight shifts. Additionally, they should be comfortable to handle and it should be easy to configure the various different weight distributions.

The initial idea was to use real solid dumbbells. The requirements however rendered them unsuitable as the vast majority of them is simply too heavy or inflexible. While typical dumbbells used for exercising offer a very nice flexibility to adjust the weight distribution, they are by far too heavy for VR interaction. Dumbbells for seniors seemed very promising with regard to this problem as they are typically lightweight but unfortunately, most of them offer little or no flexibility as the weights are commonly fixed.
The second idea was thus to use dumbbells made out of foam. While this solves the problem of the heavy weight, they proved to be too unstable as they were limber. Matters were complicated further by the fact that a dumbbell shaped object might be unsuitable for sword-like or racket-like interactions as large outerly mounted weights can interfere with movements of the wrist.
These problems lead to the third proxy concept. To solve the aforementioned problem of obstructive weights mounted on the outside, a design where weights

can be placed inside the objects was desired. The idea was thus to use pipes. These could be cut all to the same length and weights could be fixed inside of them at different locations along their main axis. They could then all weigh exactly the same and they could all have exactly the same length. They would only differ in their CM location, but the CM location would be fixed per proxy. By turning it around, each non-balanced proxy could be used for a shift to both the left and right side relative to its center. But if for example n different states of weight shift in one direction were desired, n different proxies had to be built. Moreover, an optical tracking system that uses marker constellations (also called rigid body targets) to track the objects, would require a separate target for each proxy or alternatively, a solution to flexibly mount a comparably fragile target onto the object.

The final solution that fulfills all previously mentioned requirements is an enhanced design based on the pipe-proxy idea. The difference is that in the enhanced design, a pipe is cut in several small segments. These segments are individually filled with weights by sticking or gluing. The resulting segments (also called chambers) are eventually stuck together using union connectors. With this flexible system of connected chambers, assembling a desired weight distribution along the proxy's main axis becomes easy. Through the use of lightweight pipe materials, the object weighs less than dumbbells and weights of typical game-controllers are easily achievable while significant weight shifts are still possible. The proxy can be grasped anywhere as no obstructive weights are mounted on its outside. For tracking, a single good rigid body target can be attached at one end using an additional union connector part. The CM location can be changed rapidly by re-configuring the chamber sequence. Through this, the absolute length and weight of the proxy is guaranteed to remain unchanged while just the weight shift is altered. This renders the proxy perfectly suitable for the use in the experiments, as specific weight distributions can be developed in advance. By sticking the corresponding chamber sequence, the experimenter can then quickly reassemble them during the study. The final proxy concept is illustrated in the sketch depict in Figure 3.2.

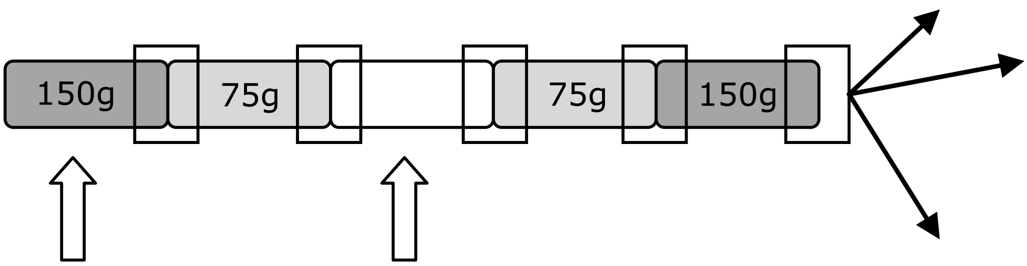

Figure 3.2: Sketch depicting the final proxy design concept. It illustrates the differently weighted chambers which are connected by union-connectors. The rigid body target is mounted on the right end and the two white arrows depict the grip- and center-grasp locations, respectively.

3.2 Implementation

This section summarizes the implementation of the introduced concepts. It reviews the hardware setup in the lab where the experiments were conducted and it gives an overview over the developed software in the subsection **Virtual Reality System**. After that, the implementation of the presented proxy object concept is described in the subsection **Proxy Objects**.

3.2.1 Virtual Reality System

This section about the implementation of the VR system covers both the **Hardware** in the lab as well as the **Software** architecture working in the background to make the interactive VR experience possible.

Hardware

The VR system for this thesis was developed and implemented in the *Ubiquitous Media Laboratory* at the *German Research Center for Artificial Intelligence (DFKI)* on the campus of *Saarland University* in Germany.

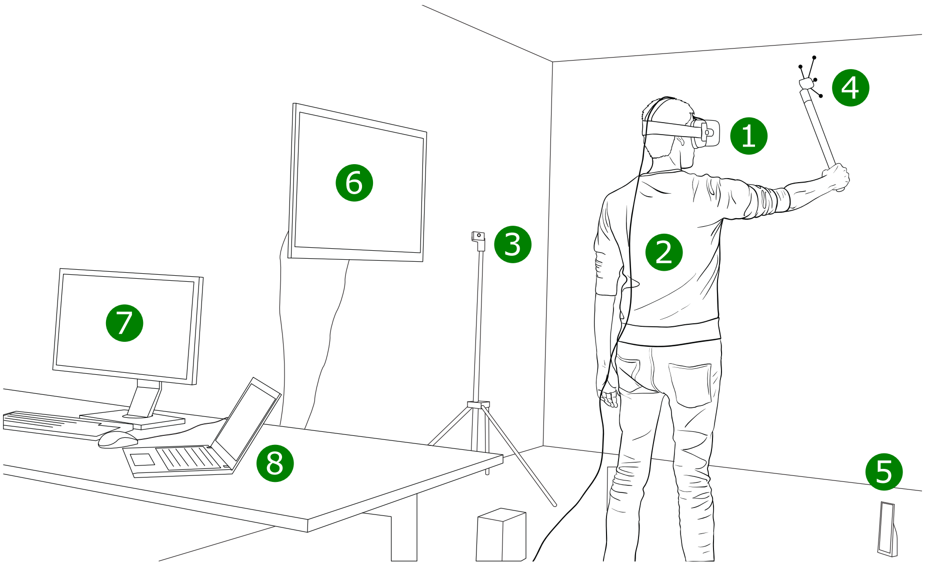

Figure 3.3: Sketch of a user performing an experiment in the laboratory setup.

The used VR-HMD was an Oculus Rift DK2 (See annotation *(1)* in Figure 3.3). All software ran on a desktop PC equipped with a 4x 3.20 GHz Intel Core i5 processor, 8 GB of RAM and a NVIDIA GeForce GTX 660 Ti graphics card. An OptiTrack motion capturing system was installed inside the lab tracking an area of approximately $3.2m \times 3.2m$. The 12 infrared cameras were mounted on a system of four traverses hanging below the ceiling, facing the tracking area in the middle of the lab. Users *(2)* entered the VE at the origin of the motion capturing coordinate system which was marked on the ground. The main PC was placed approximately $1m$ behind them and the positional tracker *(3)* of the Oculus Rift was mounted on a stand on the user's left hand side in front of him. Positional tracking of the user was done by the Oculus Rift positional tracker which tracked the HMD and the proxy objects *(4)* were tracked by the OptiTrack system. A 2.1 stereo sound system *(5)* was installed in front of the user to provide auditory feedback and a large flat-screen *(6)* on the left-hand wall mirrored the HMD's display. Through the monitor on the experimenter's table *(7)* behind the user and through the flat-screen at the wall, the experimenter was at any time able to see everything the user saw. Users and experimenters used a separate laptop *(8)* to fill in the questionnaires and a wireless presenter was used by the experimenter to remote control the experiment.

The stand to hold the proxy objects in E1 was a standard camera tripod with a custom-built mount holding the proxy horizontally. The mount was made out of a wooden panel with a holder hot glued on each end. Both holders were made out of styrofoam, cellotape and cut union connectors.

Figure 3.4: Picture of a balanced **Dumbbell Proxy** on the custom-built proxy stand.

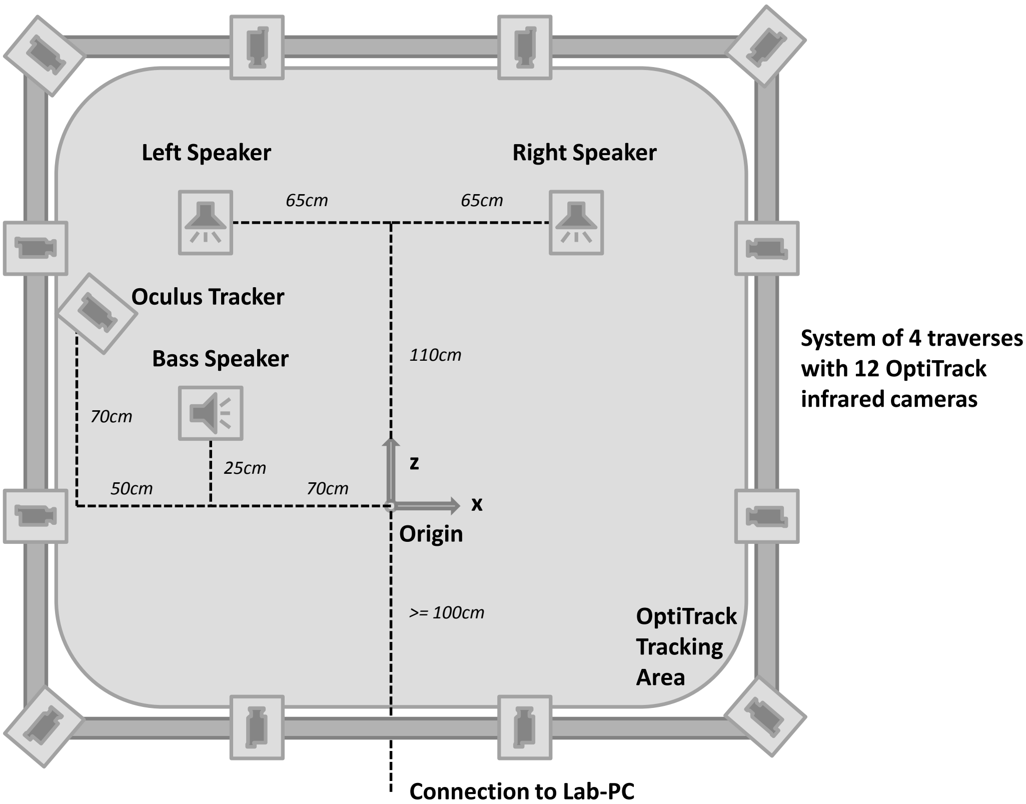

Figure 3.5: Sketch of the setup in the laboratory.

Software

The software developed for this thesis can be categorized into three main parts: the VR system integration, the implementation of the experiment software and the development of additional tools.

The VR system integration is the fundamental basis for all experiments. The main challenge was to combine various different realtime systems. The final VR system ran on the Windows 8 machine in the lab and the basic framework used for the implementation was the free version of the Unity engine 4.6, a powerful and highly performant full featured 3D game- and rendering-engine. The two major goals thus were to seamlessly integrate both the Oculus Rift DK2 with its positional tracker and the OptiTrack motion capturing system.
To fulfill the first goal, the official Oculus-Unity integration of the Oculus Rift SDK is used. It integrates the Oculus Rift HMD with its head-tracking capabilities into Unity. This enables realtime user tracking in the VE.
Fulfilling the second goal was somewhat more complex. To additionally integrate proxy objects in the virtual world, a custom OptiTrack-Unity integration was developed. With this integration, arbitrary virtual objects in Unity can be coupled to real proxy objects tracked by the OptiTrack system. Coupling hereby means, that the virtual objects follow the real objects in realtime with regard to position and rotation.
In this integration, each tracked real object is to be equipped with a rigid body target. This rigid body target is registered under an arbitrary name in the OptiTrack Arena motion capturing software. This name is used to specify the coupling in Unity, as here, a special *PositionRotationListener* script is attached to all *GameObjects* coupled to some real object. The name of the coupled real object is set in this script which allows the integration to forward position and rotation updates to the correct objects.
Upon starting the VR system, the Arena software starts tracking the rigid body targets in the tracking area and computes their position and rotation, also known as the tracking data. This tracking data is recomputed with an update rate of approximately $100Hz$. Since the tracking data for all tracked rigid bodies is compiled into a single bundle called frame, one refers to an update rate of $100fps$.
To communicate this tracking data from the motion capturing system to Unity, a low-latency middleware approach was chosen. The Arena capturing software streams the frame data at its $100fps$ to a middleware developed in C#. The C# middleware uses the OptiTrack NatNet 2.7 SDK to receive the frame data from Arena. Subsequently, the data of all rigid bodies is extracted from the received frame and sent in a JSON-encoding via UDP to Unity. This data is finally received by the OptiTrack integration scripts in Unity which implement a publish-subscribe pattern for the rigid body updates. The already mentioned scripts attached to the virtual twin-objects subscribe to the integration to receive updates of the coupled rigid bodies. Upon reception of new rigid body data from the middleware via UDP, the received information of the rigid bodies is decoded. Directly after that, all *GameObjects* listening to the contained rigid bodies are

notified via an internal push-update notification mechanism. The scripts on the *GameObjects* then immediately update the objects' virtual position and rotation in Unity.

The architecture of the OptiTrack-Unity integration is depict in Figure 3.6. It allows for low-latency realtime coupling between proxies and virtual objects and meets all defined requirements. As the OptiTrack-Unity integration makes use of multi-threading and locking mechanisms, it seamlessly integrates into Unity's internal update structure and still allows for very high rendering frame rates.

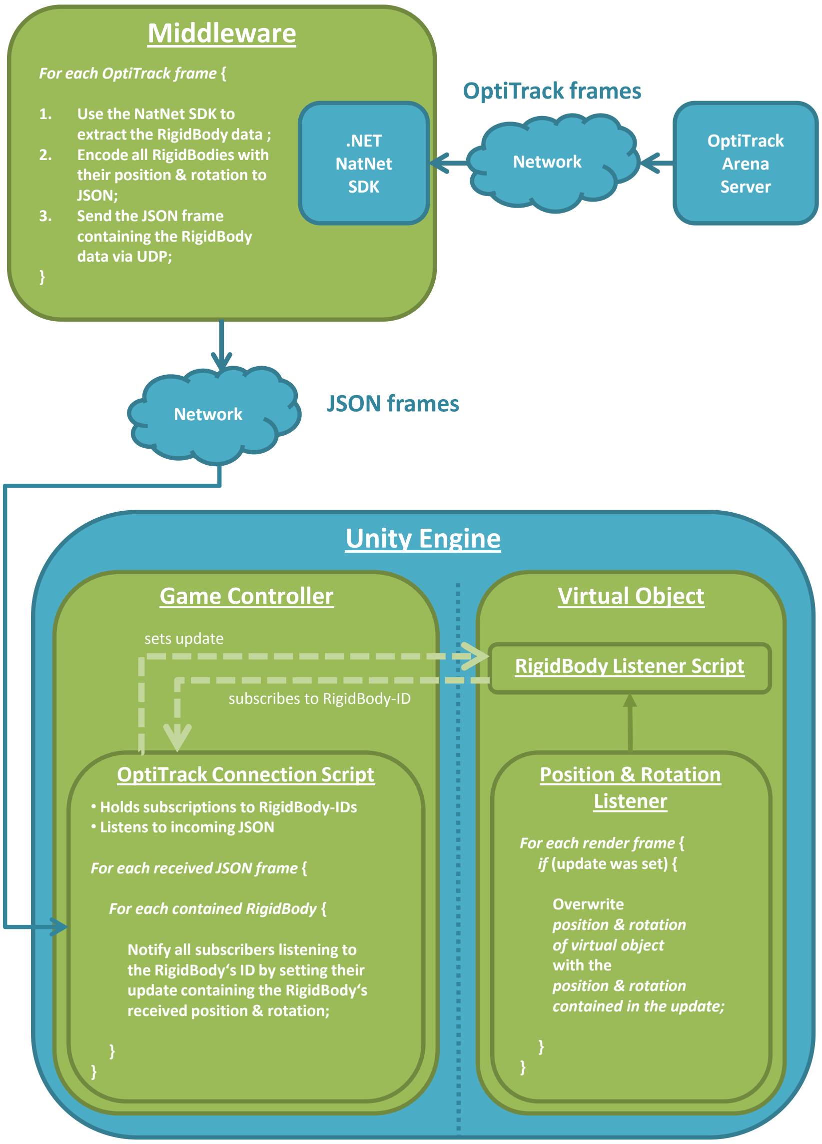

Figure 3.6: The software architecture of the OptiTrack-Unity integration. Green modules were developed and implemented for this thesis, blue modules indicate preexisting software.

Beyond the software for the integration of the VR system components, the software for the actual experiments was developed. All experiments were likewise implemented in C# and Unity. The scenes and VEs were built using only self-made 3D models or free models and textures from Unity's Asset Store [5] and TurboSquid [6]. The games played in the course of the experiments were implemented by various scripts and all measurements (times, angles, distances etc.) were directly computed in-engine and saved to file in *Comma Separated Values* (CSV) tables.
While the neutral scene in E1 consisted primarily of a skybox and a large plane, the proxy object and the target rig, the second environment was more complex. The desert environment made use of Unity's physics engine as interactive cubes hung at virtual linear springs. To generate wooden sticks of arbitrary lengths and weights, custom scripts modified self-made and imported 3D models.
Besides the ability to play the experiments live in the lab, a complete recording and playback mechanism was implemented. It allows to record entire experiments by saving the complete movement of the proxy objects and the user's head. This offered the possibility to play back entire sessions in realtime and thus to re-produce measurements. Although it was not necessary for the conducted experiments, this mechanism even allowed to conduct measurements post hoc, not implemented at the time the experiment was performed.

Aside from the implementation of the VR system and the experiments, several tools were developed in the course of this thesis that aim to ensure no results were lost, that results could be reproduced and that made the handling of the results easier.
In addition to the already mentioned recording and playback mechanism implemented in Unity, the C# middleware also implements a recording and playback feature. It allows to record motion capturing sequences and to save them to file in order to play them back at a later point in time. This allowed to develop and test the system even if no motion capturing system was available as the middleware could simulate previously recorded sequences by streaming them again at $100fps$.
Besides that, a vast amount of measurements were saved during the experiments which made the resulting CSV tables become very large and hard to survey. To ease the statistical evaluation, a simple scripting format was invented in line with a small tool that could read and execute the scripts. It was used to generate a set of small and neat tables summarizing the most important measurements from a few huge tables produced by the experiment software.
Finally it is worth to mention that the developed OptiTrack-Unity integration was compiled to a *unitypackage* which allows to directly import the integration and examples into other Unity projects. In conjunction with a brief manual and the middleware, this makes the realtime coupling system available for other research as well.

[5] https://www.assetstore.unity3d.com/
[6] http://www.turbosquid.com/

3.2.2 Proxy Objects

The implementation of the proxy design concept is described in the following. Two proxy types are introduced since both experiments of the main study used different proxy objects. As they only differ in parameters such as the amount of chambers, chamber size, chamber weight etc. the section **General Implementation** at first describes the common features of all built proxies. The sections following up then detail on the different features of the **Dumbbell Proxy** used in E1 and the **Stick Proxy** used in E2.

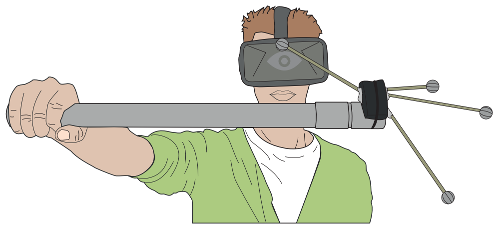

Figure 3.7: Sketch of a user interacting with a **Stick Proxy** in the experimental VR setup. The rigid body tracking target is fixed on the proxy's upper end.

General Implementation

The input devices in the experiments were rod-shaped proxy objects, equipped with different weight distributions as described in the introduction of the proxy design concept.
The proxies are made out of cheap and readily available materials that are easy to handle and to assemble and that can be found e.g. in a do-it-yourself store. The proxy body consists of cut *Polyvinyl chloride* (PVC) pipe parts (the chambers) and PVC union connectors. This makes the proxy body lightweight and sufficiently robust. The chambers are filled with steel bolts (each ca. $112g$), steel nuts (each ca. $41g$) and steel slices (each ca. $10g$). The size of the steel parts is chosen to exactly match the pipe's inner diameter. In this way, sticking suffices and no gluing is necessary. The steel weights can be inserted arbitrarily deep into the chambers which allows for fine adjustments of the distribution. In order to shift the weight further outwards at the chamber's ends, a partially inserted steel bolt can be used to hold slices and nuts. Eventually, the different chambers are connected with suitable union connectors to build the complete proxy. By changing the chamber ordering along the proxy's main axis, different weight distributions are produced.

To track the proxies as rigid bodies with the OptiTrack motion capturing system, suitable targets have to be attached to them. Hence a union connector with a very ligthweight custom-built rigid body target fixed on it can be plugged onto the proxy's outermost chamber. It consists of thin spits of wood holding infrared reflecting markers and a base of styrofoam. The markers are arranged asymmetrically in 3D space. Inspired by research on optimal rigid body target design [61], the markers were placed so that the distance between each two of them was unique and sufficiently different from the distances of all other pairs. This target design allowed for robust tracking.

Dumbbell Proxy

The dumbbell proxy used in the first experiment (E1) is a perfect demonstration of a multi-chamber construction. It uses a 4 chamber design with 4 connectors and and a fifth holding the rigid body target. The complete proxy has a length of $73cm$ and the empty proxy body without steel parts weighs $194g$. To produce the weight shifts, a total of $306g$ of steel weights is distributed in the two outermost chambers. Thus the resulting total weight is $\approx 500g$.
For E1, three different **Dumbbell Real** weight distributions were required: a balanced version with the CM at the **Center** location (**D-R-C**), a **Half-Right** shifted version (**D-R-HR**) with the CM shifted by $10cm$ to the right and a **Right** shifted version (**D-R-R**) with the CM shifted by $20cm$ to the right. To reduce the time spent during the experiment re-configuring and sticking the proxies, three different proxies were assembled in advance. They all feature different CM locations but they all have exactly the same weight and length. In this way it sufficed to stick the rigid body target onto the new proxy when changing it in between experimental runs.
The exact CM location shifts can be seen in Figure 3.8 which also shows a picture of the proxy objects used in E1 without the rigid body target mounted on them. The inserted steel parts are indicated above the two outermost chambers.

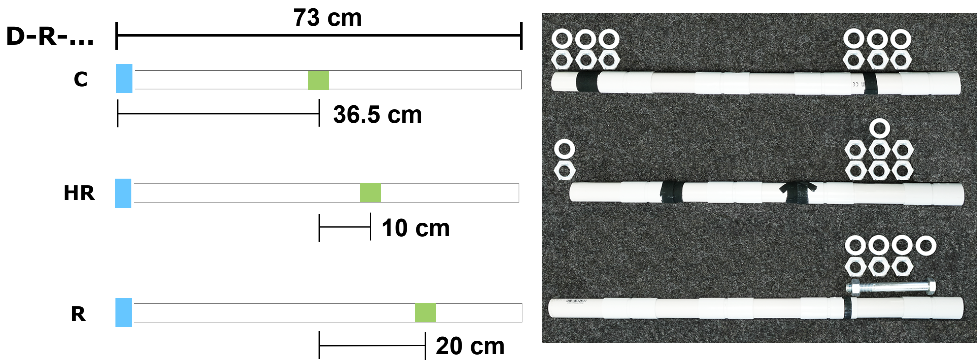

Figure 3.8: The concept drawings on the left show the **Dumbbell Proxy** objects with the corresponding CM locations (green) and the location of the tracking target (blue). The notation **D-R-...** encodes the **D**umbbell's **R**eal shift to the **C**enter, **H**alf-**R**ight or **R**ight. The picture on the right shows the real proxies with the inserted steel weights.

Stick Proxy

The proxies used in the second experiment (E2) represent special cases of the introduced proxy design concept. They feature a single-chamber design, which means that a single cut PVC pipe is used in conjunction with a union connector fixing the rigid body target at the upper end. The complete proxy is $50cm$ long and the empty proxy weighs $102g$. To produce the weight shifts, 3 steel nuts with a total weight of $123g$ were added yielding a total proxy weight of $\approx 225g$.
As three different **Stick Real** weight distributions were required for E2, namely a **Grip**-heavy (**S-R-G**), a **Mid**-heavy (**S-R-M**) and a **Top**-heavy (**S-R-T**) shift, two proxy objects were assembled. As they both consist of a single chamber, only the weight distribution inside this chamber differs. The center-heavy proxy concentrates the steel weights at its center and the second proxy concentrates the weights at one end of the chamber. By turning this second proxy around and by swapping the rigid body target to the other end, the user could grasp it either at the end where the weight is concentrated or on the opposite. In this way, it could be used to represent both a grip- and a top-heavy object.
The exact CM shifts and the real proxies together with the inserted steel nuts can be seen in Figure 3.9.

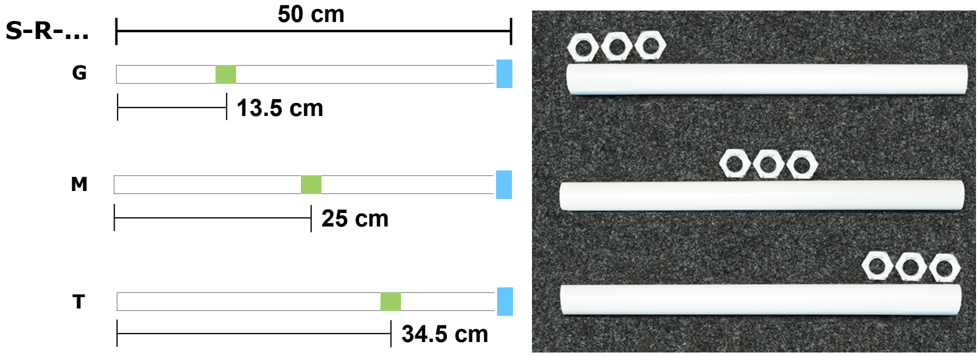

Figure 3.9: The concept drawings on the left show the **Stick Proxy** objects with the corresponding CM locations (green) and the location of the tracking target (blue). The notation **S-R-...** encodes the **S**tick's **R**eal shift to the **G**rip, **M**id location or the **T**op. The picture on the right shows the two real proxies with the inserted steel weights. The bottommost object is the topmost proxy after turning it around.

Chapter 4
Experiments

This chapter describes the conducted experiments of the main study in detail. At first, information about the participants and the apparatus for both experiments is provided. In the following, a detailed description of both experiments' procedures and designs is given. Along with that, the hypotheses to be verified by the experiments are stated.

4.1 Participants

For the main study, 24 volunteer participants (6 female) were recruited from the local university campus, which received 10 Euros each for the participation in both experiments. The age of the participants ranged from 20 years to 58 years ($M = 25.96$ years, $SD = 7.36$ years), their body height ranged from $167cm$ to $197cm$ ($M = 178.96cm$, $SD = 7.28cm$) and their eye height over ground ranged from $155cm$ to $184cm$ ($M = 167.42cm$, $SD = 7.36cm$). Six of them wore glasses or contact lenses and all were right-handed. Regarding gaming experience with 3D video games, some participants had no experience, some stated to play rarely and irregularly while others stated to play on a very regular basis. Overall, all types of gaming behavior were represented on a scale from 0 (= never) to 6 (= regularly) ($M = 2.79$, $SD = 2.32$). Concerning VR technology (on the same scale), more than 87% stated to have no or only very little experience ($M = 1.04$, $SD = 1.49$), and even over 83% had no VR experience at all with interactive objects such as proxies ($M = 0.37$, $SD = 1.01$), not including common input devices such as joysticks, mouse or keyboard. Besides that, three out of four participants stated to do sports regularly at least once a week.

4.2 Apparatus

The VR system in the laboratory and the proxy objects introduced in the chapter **Concept** served as experimental platform. For a more detailed description of the involved hardware and software, refer to section **Implementation** in the previous chapter.

Figure 4.1: Picture of a user performing *Experiment 2: Length & Weight* (E2).

4.3 Experiment 1: Warm-Up & Lift-Up

The first experiment focused on the **first goal** of this thesis: the investigation of the influence of proxy *weight distribution* on VR user interaction and behavior. To study the effect of visual-haptic stimuli discrepancies (**Goal 1-a**) and the role of directional weight shift (**Goal 1-b**), a set of hypotheses about the weight distribution's influence was formulated. These hypotheses are summarized in the following:

- **H1.1**: For VR proxy interaction in general and especially for the *perceived realism* and *unexpected object behavior*, the *direction* of the proxy weight shift is more important than the *absolute extent* of the shift. (**Goal 1-b**)
- **H1.2**: The *height (roll) angle error increases* with the level of real-virtual *weight distribution mismatch*. (**Goal 1-a**)
- **H1.3**: *Handling comfort* and *perceived realism decrease* when the level of real-virtual *weight distribution mismatch increases*. (**Goal 1-a**)
- **H1.4**: The risk of experiencing *unexpected object behavior increases* with the level of real-virtual *weight distribution mismatch*. (**Goal 1-a**)

These hypotheses are to be verified by the first experiment (E1) which is described in detail in the following. As already introduced, it consists of two successive phases (P1 followed by P2) which both involve interaction with the dumbbell proxies.

4.3.1 Procedure

After being welcomed, the participant was briefed about the technical setup and the course of the first experiment. At the beginning, the body height and eye level of the participant were measured and the participant was asked to fill out a pre-study questionnaire on a prepared laptop. This questionnaire collected demographic data and asked about previous experience with VR applications and proxy interaction. Upon completion of the questionnaire, descriptions of the first phase (*Phase 1: Warm-Up* (P1)) and the second phase (*Phase 2: Lift-Up* (P2)) were carefully read by the participant. The measured eye level was in the meantime used by the experimenter to adjust the height of the stereo cameras in the VE and to adjust the height of the stand in front of the participant. This ensured that the participant did not feel smaller or larger in the VE and it ensured equal conditions for both small and tall people. Finally, the experimenter prepared the Oculus HMD. Possible questions of the participant were directly answered by the experimenter. To ensure unbiasedness however, the proxy objects were never shown. In general, all questionnaires as well as all instructions in both experiments were given in the native language of the participant.

Phase 1: Warm-Up

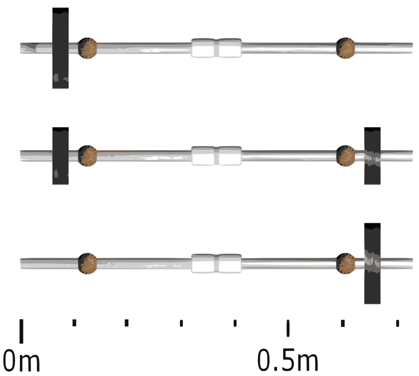

Figure 4.2: Orthographic picture of the virtual dumbbell objects used in *Experiment 1: Warm-Up & Lift-Up* (E1).

At the beginning of the *Warm-Up* phase (P1), the participant put on the Oculus HMD and entered the VE at the origin of the capturing system. After the experimenter started the VR software, he asked whether the participant was feeling well and was able to read a standard warning note displayed in the VE. If the participant could read the small warning note, it was ensured that he could also see the targets and objects in the experiment reasonably well.

P1 consisted of 3 runs played in succession. In each run, the target-pointing game of the pilot study introduced in the **Concept** was played with a different weight distribution. As P1 intended to make the participants familiar with the VE and the proxy interaction, no real-virtual weight distribution discrepancies, i.e. CM mismatches, were involved. In other words, the CM location of the virtual dumbbell and the real proxy object always matched. To learn about the characteristics of the virtual dumbbell, 3 runs were played: the first with a balanced, the second with a right shifted and the last with a left shifted dumbbell. Before each run, the experimenter placed the corresponding proxy object horizontally on the stand in front of the participant. Then he helped the participant to grasp the rod-shaped proxy at its center. Once the participant had grasped the proxy, a countdown of 5 seconds started. The participant was only allowed to lift the proxy after the countdown reached zero and a gong sounded. The goal of the game was then to charge all 8 single-targets twice by holding the wooden balls on the virtual dumbbell inside the spheres. The single-targets were displayed in a randomized order and in between two single-targets, the double-target had to be charged. The time needed to fully charge a target (the dwell time) was set to $800ms$. While walking in the VE was not allowed, the participant was free to look around and he could perform arbitrary movements with the proxy. Once all targets were processed, a double-gong sounded and the run was completed. After the completion of each run, the participant answered post-task questions posed by the experimenter while still holding the proxy object in his hand. Finally, the participant gave the proxy object back to the experimenter, who then prepared the next run.

Phase 2: Lift-Up

As soon as all 3 runs in P1 were completed, the single-targets disappeared and the double-target relocated a few centimeters over the participant's head. In this even simpler environment, the second phase *Lift-Up* (P2) took place.

P2 again consisted of multiple runs each played with a different real-virtual weight distribution combination. In contrast to P1, P2 also featured combinations where the virtual weight distribution differed from the real weight distribution in that the CM location of the dumbbell and the proxy did not match. As introduced in the **Concept**, all possible combinations of 3 different visually implied weight distributions and 3 physical proxy weight distributions were played by each participant. The virtual dumbbells were modeled so that, if physically built, their CMs were located exactly at the desired positions. The computations and assumptions for these models can be found in the appendix **Virtual Dumbbell Design**. The **Dumbbell**'s **Virtual** weight distributions used here were **Left** (abbreviated with **D-V-L**) with a CM shifted by $20cm$ to the left , **Center** (**D-V-C**) with the CM at the center of the dumbbell and **Right** (**D-V-R**) with the CM shifted by $20cm$ to the right. The **Dumbbell**'s **Real** proxy weight distributions were **Center** (**D-R-C**) with the CM at the center, **Half-Right** (**D-R-HR**) with the CM shifted by $10cm$ to the right and **Right** (**D-R-R**) with the CM shifted by $20cm$ to the right. As this yields 9 combinations, each participant played 9 runs in succession.
Each single run in turn consisted of 3 repetitions. In each repetition, the goal was to lift the dumbbell horizontally in a pleasant, quick and continuous movement out of the stand into the double-target to charge it. Similar to P1, the experimenter placed the proxy on the stand and helped the participant to grasp it. The lift-up was then performed when a countdown reached zero. After each single lift-up, the participant gave the proxy to the experimenter who then placed it again horizontally on the stand for the next repetition.

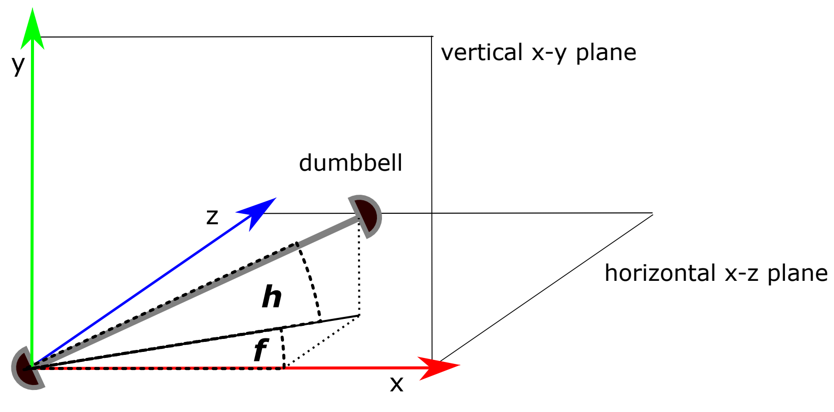

Figure 4.3: Sketch of the measured *height angle* (***h***) and *forward angle* (***f***).

A large set of measurements, most importantly the height (roll) angles[7] and forward (yaw) angles[8] of the dumbbell at various times during lift-up as well as a complete recording of each run were saved for the evaluation. For this, virtual measurement planes were introduced in P2 which can be seen in the visualization in Figure 4.4. 10 virtual invisible planes were distributed in the space between the start-plane (located directly above the proxy resting horizontally on the stand) and the double-target which had a vertical distance of $1m$. Each time the left wooden ball on the dumbbell passed a plane, the measurements, including the height and forward angle, were taken and saved. Thus during each lift-up, measurements were taken at vertical intervals of ca. $11.1cm$.

When 3 consecutive lift-ups, and therewith a run, was completed, the participant answered the same post-task questions as in P1 and then proceeded after a 1 minute break with the next run. The experimenter changed the real-virtual weight distribution only between runs according to a counterbalanced order prepared in advance. After all 9 runs, and therewith the first experiment (E1), were completed, a short break of five minutes followed in which the participant took off the Oculus HMD to read the instructions for the second experiment (E2).

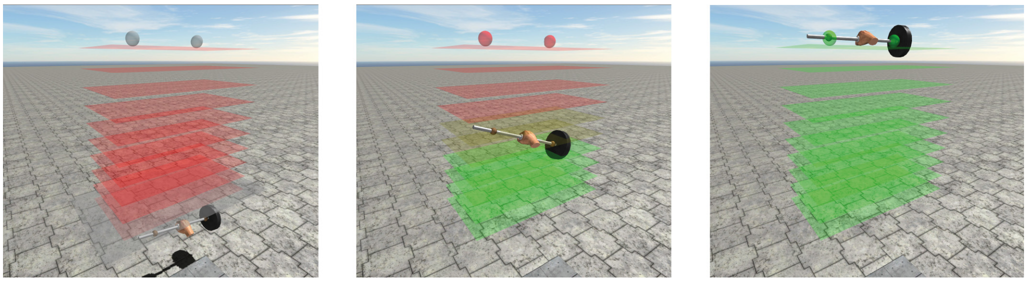

Figure 4.4: Visualization of the measurement process in the *Lift-Up* phase. Each image depicts the 10 measurement planes and the double-target. Planes not passed by any wooden ball on the dumbbell are colored red, planes passed by only one ball on the dumbbell are colored orange and planes passed by both wooden balls are colored green. Image 1 depicts the situation before the lift-up, image 2 shows the situation during lift-up and image 3 illustrates the moment when the double-target is charged.

[7]The *height* or *roll angle* of the dumbbell object is the angle between the rod's main axis and the horizontal plane spanned by the *right-vector* and the *forward-vector* ($\overrightarrow{x}$ and $\overrightarrow{z}$ in a left handed coordinate system).

[8]The *forward* or *yaw angle* of the dumbbell object is the angle between the rod's main axis and the vertical plane spanned by the *right-vector* and the *up-vector* ($\overrightarrow{x}$ and $\overrightarrow{y}$ in a left handed coordinate system).

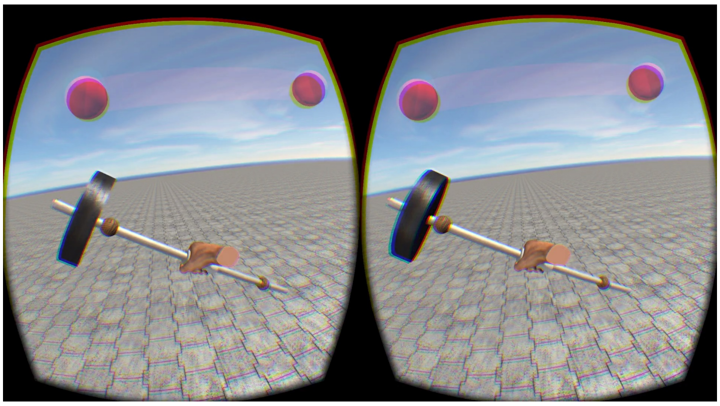

Figure 4.5: Screenshot of a user's view during the *Lift-Up* phase. The virtual weight distribution is left shifted (**D-V-L**) while the real weight distribution is right shifted (**D-R-R**). As a consequence of this mismatch, the user struggles to lift the dumbbell horizontally into the double-target, as can be clearly seen in the screenshot.

4.3.2 Design

As the *Warm-Up* phase was equivalent to the conducted **Pilot Study** which did not yield significant results, it was only supposed to familiarize the participants with the VE and the proxy interaction in the main study. Thus the focus of E1 lay on the *Lift-Up* in P2.

The *Lift-Up* experiment in P2 was a 3×3 within-subjects full factorial design. The two factors in this experiment were the dumbbell's

- *virtual* ($20cm$ left, center, $20cm$ right)
- *real* (center, $10cm$ right, $20cm$ right)

CM locations.

The dependent variables were

- the measured height angles for **H1.1** and **H1.2**
- the measured forward angles for **H1.1**
- the ratings of the post-task questions for **H1.1**, **H1.3** and **H1.4**

According to a *Latin Square* design, the order of the 9 weight shift configurations was counterbalanced across all participants.

4.4 Experiment 2: Length & Weight

The second experiment (E2) was dedicated to the **second goal** of this thesis: the investigation of the proxy *weight distribution*'s influence on the user's perception of virtual objects. Similar to the first experiment, E2 also consisted of two consecutive phases: P3 and P4.
In P3, the influence of weight distribution on perceived object *form* was investigated (**Goal 2-a**) and P4 studied the influence on the perceived *weight* or *heaviness* of virtual objects (**Goal 2-b**).
The main hypotheses corresponding to these goals are:

- **H2.1**: The perceived *length* of an interactive virtual object can be controlled by the *weight distribution* of the proxy object.
- **H2.2**: The perceived *weight* of an interactive virtual object can be controlled by the *weight distribution* of the proxy object.

The second experiment aims to verify these hypotheses. For this, both phases of E2 involve interaction with the introduced stick proxies.

4.4.1 Procedure

Figure 4.6: Screenshot of the environment in *Experiment 2: Length & Weight* (E2).

During a break of 5 minutes after completing the first experiment, the participant carefully studied the instructions of the third phase (*Phase 3: Length* (P3)) and the fourth phase (*Phase 4: Weight* (P4)). Any remaining questions were answered by the experimenter and as soon as the tasks in P3 and P4 were clear, the participant put on the Oculus HMD and entered the VE again.
The VE in P3 and P4 differed from the VE of the first experiment. Here, the

participant was put into a virtual desert environment. During the experiment, he was standing in front of a wooden scaffold on which four different cubes were hanging on easily ripping rubber bands. Figure 4.6 shows a screenshot of the scene. As this environment had a more natural appearance, it resembled a game-like setting more closely. This was intended as the second experiment aimed to study the user's perception of virtual objects in conditions similar to the areas of application for proxy interaction like e.g. gaming, training or simulation environments.

Phase 3: Length

In the course of P3, the participant was provided with several different proxy objects in succession and his task was to choose among different visual representations the one that best matched his haptic impression. For this, the **Stick Proxy** objects with their 3 different weight shifts along the stick's main axis were used. The participant however did not know about the differences between the proxies nor did he know how many different physical objects were involved. In the virtual domain, the visually perceived objects in P3 were wooden sticks that only differed in length. Thus by choosing the virtual object that best matched the haptic impression, the user implicitly stated the perceived object length.
To ensure that all participants had an equivalent reference, each participant initially interacted with the so called *reference object*. This means, the participant held the *mid-heavy* stick proxy (**S-R-M**) in his hand while in the VE, he saw his hand holding a wooden stick of *medium length*. To familiarize with the reference object and its impression, the participant could move, swing and wield the object around freely to get a feeling for it.

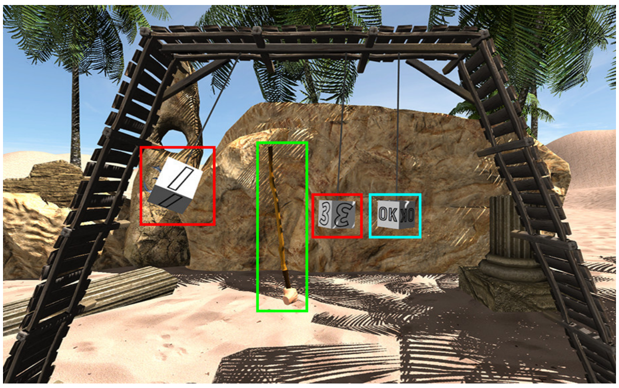

Figure 4.7: Illustration showing the wooden scaffold with the cubes hanging on rubber bands. The currently selected object is object "2" (the wooden stick of *medium length*), as can be seen in the green box. The alternative objects "1" and "3" can be chosen by knocking off the corresponding cubes in the red boxes. The "OK" cube in the blue box is used to submit the selection.

After fixing the impression of the reference object on the mind, the participant's actual selection tasks began. In 6 subsequent trials, the participant received each weight-shift condition of the stick proxy twice ($2\times$ *grip-heavy* (**S-R-G**), $2\times$ *mid-heavy* (**S-R-M**), $2\times$ *top-heavy* (**S-R-T**)) in a counterbalanced order. To receive a proxy, the participant stood upright facing the wooden scaffold with his arms hanging relaxed. The experimenter took the prepared stick proxy with the corresponding weight shift and placed it in the participant's palm. As soon as the participant grasped the proxy, the experimenter started the trial and the virtual object in the user's hand became visible. The initially held virtual object was always the wooden stick of medium length as it was the reference. The available selections for length then were: a short ($0.5m$), medium ($1m$) and a long ($2m$) virtual wooden stick. The virtual objects can be seen in Figure 4.8. To change the virtual object in the hand, the cubes on the rubber bands acted as a selection menu. After knocking off the corresponding cube with the virtual wooden stick, the virtual object in the participant's hand was substituted by the selected stick. Here, cube "1" corresponded to the short stick, cube "2" to the medium and cube "3" to the long stick. The participant was free to try out all three virtual wooden sticks without any time constraint until the one that matched the haptic impression best was identified. Upon deciding for a virtual stick, the participant selected it and then knocked off the "OK" cube with it to submit the selection. As the selection completed the trial, the participant then gave the proxy back to the experimenter and the next trial was performed.
Besides a complete recording of the experiment, the most important measurement was the participant's final selection in each trial.

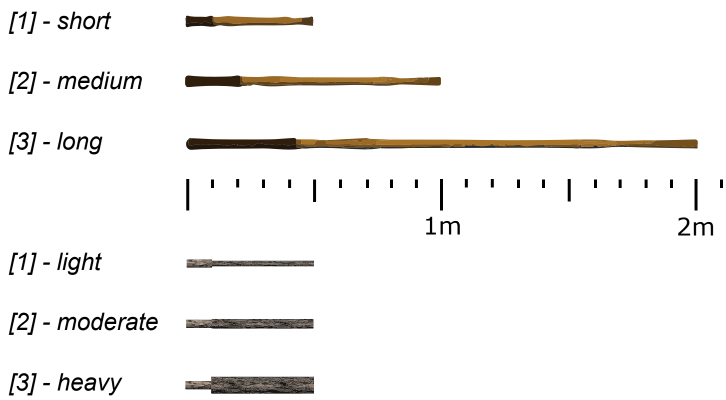

Figure 4.8: Orthographic picture of the different virtual wooden sticks used in *Experiment 2: Length & Weight* (E2)

Phase 4: Weight

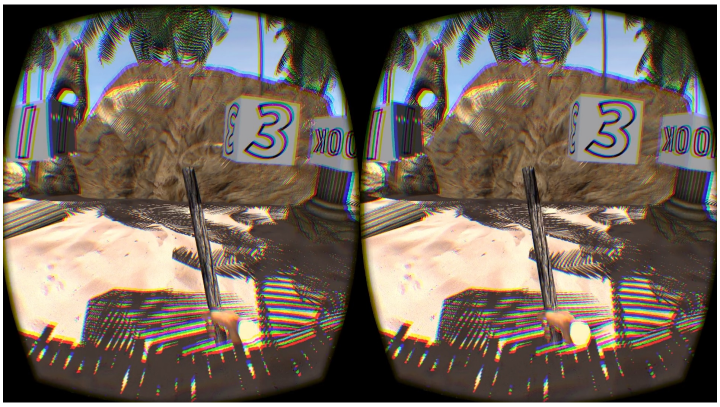

Figure 4.9: Screenshot of a user's view during *Phase 4: Weight* (P4).

The procedure of the last phase P4 of the second experiment is equivalent to the procedure of P3 except that the virtual objects now only differed in their volume. The virtual objects seen by the participant were short wooden sticks with a handle of fixed diameter. The upper parts of the different virtual wooden sticks however varied in their volume and thus in their visually implied weight or heaviness. The objects are depict in Figure 4.8. With the cubes, participants could choose between a light ($0.00015m^3$), a moderate ($0.00045m^3$) and a heavy ($0.00135m^3$) wooden stick. Of course, the *medium* object in combination with the *mid-heavy* stick proxy was used again for the *reference* impression.

After P3 and P4, and therewith the second experiment, was successfully performed, the participant took off the Oculus HMD in order to fill out a SUS-Presence-Questionnaire and further post-study questions.

4.4.2 Design

The second experiment was a 3×2 within-subjects full factorial design. Here, the factors were

- *Real Weight Distribution* (top-heavy, mid-heavy, grip-heavy)
- *Object Property* (length, weight)

The dependent variable was

- the perceived length or weight on a discrete scale from 1 to 3 implicitly given by the final selection for **H2.1** and **H2.2**

The real weight distributions were counterbalanced by a *Latin Square* ordering.

Chapter 5
Results

This chapter summarizes and illustrates the most important results of the main study introduced and described in the previous chapters. This includes descriptive statistics of the objective measurements and the subjective ratings. Additionally, the results of the conducted statistical significance tests are summarized. The chapter is structured as follows: the results of the first experiment (*Experiment 1: Warm-Up & Lift-Up* (E1)) are compiled in the first section followed by the results of the second experiment (*Experiment 2: Length & Weight* (E2)) in the second section. The last section eventually provides the results of the SUS-score and the post-study questionnaire.

5.1 Experiment 1: Warm-Up & Lift-Up

This section presents the results of the first experiment, more precisely the results of the second phase (*Phase 2: Lift-Up* (P2)). As it turned out during the **Pilot Study** that the first phase (*Phase 1: Warm-Up* (P1)) is non-optimal for the investigation, it was only supposed to familiarize the participants with the VE and proxy interaction in the main study. Thus, this chapter does not detail on the results of P1 but focuses on the improved lift-up experiment in P2.

Configuration	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
D-R-	**R**	**R**	**R**	**C**	**C**	**C**	**HR**	**HR**	**HR**
D-V-	**R**	**C**	**L**	**R**	**C**	**L**	**R**	**C**	**L**
Discrepancy	**D0**	**D2**	**D4**	**D2**	**D0**	**D2**	**D1**	**D1**	**D3**

Table 5.1: Overview of all configurations played in *Phase 2: Lift-Up* (P2) with their real and virtual weight distribution and their corresponding level of discrepancy.

Before diving into the actual results, it is important to clarify two important terms frequently used in the analysis: *configuration* and *discrepancy*. The combination of one of three real weight shifts (center: **D-R-C**; half right: **D-R-HR**; right: **D-R-R**) with one of three virtual weight shifts (left: **D-V-L**; center: **D-V-C**; right: **D-V-R**) in P2 is called *configuration*. Each *configuration* has an associated *level of discrepancy*. The combination of the three real and the three virtual weight distributions in P2 yields 5 different *levels of discrepancy* with different CM mismatches ($0cm$: **D0**; $10cm$: **D1**; $20cm$: **D2**; $30cm$: **D3**; $40cm$: **D4**). Table 5.1 summarizes all 9 *configurations* (**A** to **I**) played in P2 and the corresponding *discrepancy levels*. Moreover, these configurations can be grouped in real and virtual weight distribution groups called R1, R2, R3 and V1, V2, V3. Table 5.2 summarizes the configurations in each group and their common distribution.

Group	Common Distribution	Configurations
R1	**D-R-C**	**D, E, F**
R2	**D-R-HR**	**G, H ,I**
R3	**D-R-R**	**A, B ,C**
V1	**D-V-L**	**C, F, I**
V2	**D-V-C**	**B, E, H**
V3	**D-V-R**	**A, D, G**

Table 5.2: Definition of R1, R2, R3, V1, V2 and V3.

5.1.1 Forward Angle & Height Angle

The task in P2 was to lift the virtual dumbbell horizontally from a stand into a double-target at a distance of about $1m$. The *forward* and *height* angles were measured at 10 invisible planes with a vertical separation of ca. $11.11cm$ when the dumbbell's left wooden ball passed the plane. They are denoted in degree measure. The angle values used in the following are averaged over all 10 planes and all 3 consecutive lift-up repetitions per configuration unless noted otherwise.

Forward Angle

The average forward angles for each configuration can be seen in Figure 5.1. One-Way ANOVA tests concerning the different real and virtual weight distribution groups and the level of discrepancy only showed a significant influence of the real weight distribution on the forward angle ($F = 6, p < 0.01$) for $\alpha = 0.05$. For further analysis, the groups of equivalent real weight distributions were concerned (R1: ($M = -0.27°$, $SD = 2.22°$); R2: ($M = -1.39°$, $SD = 2.73°$); R3: ($M = -2.01°$, $SD = 2.90°$)). Kolmogorov-Smirnov normality tests rendered pairwise t-tests applicable. The difference in the forward angle between R1 and R3 ($T = -3.68$, $p < 0.01$) and between R1 and R2 ($T = 2.62$, $p < 0.015$) was significant on a significance level of $\alpha = 0.05$.

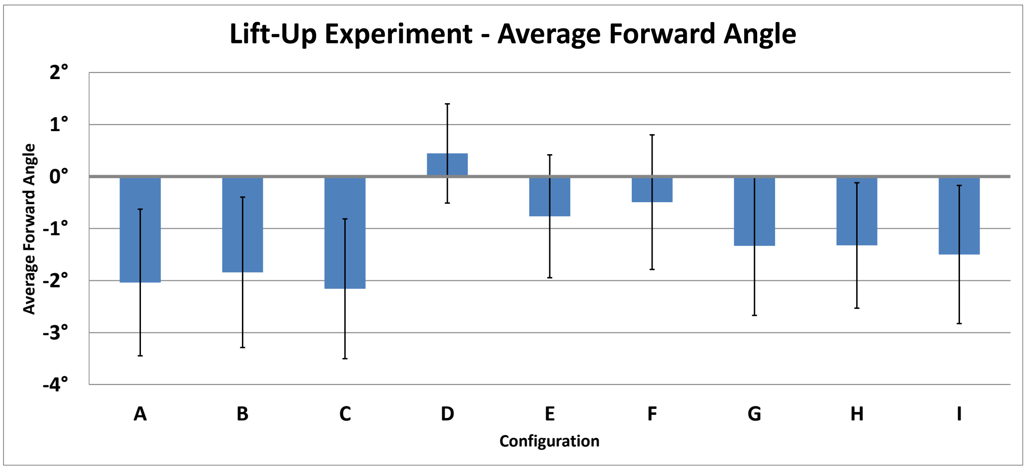

Figure 5.1: Average forward angles for each configuration in *Phase 2: Lift-Up* (P2) with 95% confidence intervals.

Height Angle

In line with the forward angle, the height angle was analyzed with One-Way ANOVA tests as well. The average height angle per configuration can be seen in Figure 5.2. Here, the ANOVA tests revealed a significant influence of the visual weight shift ($F = 18$, $p < 0.01$), real weight shift ($F = 40$, $p < 0.01$) and level of discrepancy ($F = 12$, $p < 0.01$) on the error distance of the height angle[9].
Concerning the groups of equivalent real weight distribution (R1; R2; R3), equivalent virtual weight distribution (V1; V2; V3) and equivalent discrepancy level (D0; D1; D2; D3; D4), further Kolmogorov-Smirnov normality tests showed pairwise t-tests to be applicable. These pairwise t-tests among R1, R2, R3 and V1, V2, V3 revealed all real and virtual distribution groups, respectively, to be significantly different from each other (with at least $p < 0.01$). A more detailed investigation of the groups R1, R2 and R3 tested whether a change in the visual stimulus alone could significantly affect the error in the height angle when the haptic stimulus, i.e. the real weight distribution, remained unchanged. For this, the three configurations of each group (i.e. **D**, **E** and **F** for R1 etc.) were tested pairwise.

Equivalent tests were conducted to check if a change in only the haptic stimulus could significantly affect the error when the visual stimulus was fixed. For this, the three configurations of each group V1, V2 and V3 were tested pairwise against each other (i.e. **C**, **F**, and **I** for V1 etc.). The results of Kolmogorov-Smirnov tests recommended to use Wilcoxon signed-rank tests for the comparison. Table 5.3 provides the corresponding results. In almost all cases, a significant influence of the variable stimulus could be verified.

[9] As the task was to lift the dumbbell horizontally, every non-zero height (roll) angle can be regarded as an error. Hence with *error distance*, the actual magnitude of the height angle is meant.

Figure 5.3 depicts the influence of the weight distribution mismatch on the height angle error in the first lift-up. Although fluctuating and not strictly monotonically, the average height angle error increases with increasing mismatch, as the linear regression line shows. The error was at its maximum in configurations with maximum discrepancy.

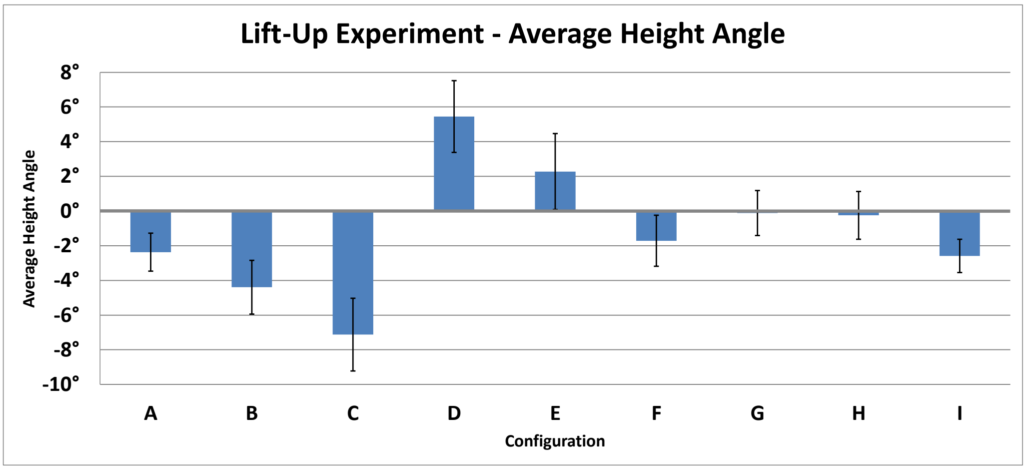

Figure 5.2: Average height angles for each configuration in *Phase 2: Lift-Up* (P2) with 95% confidence intervals.

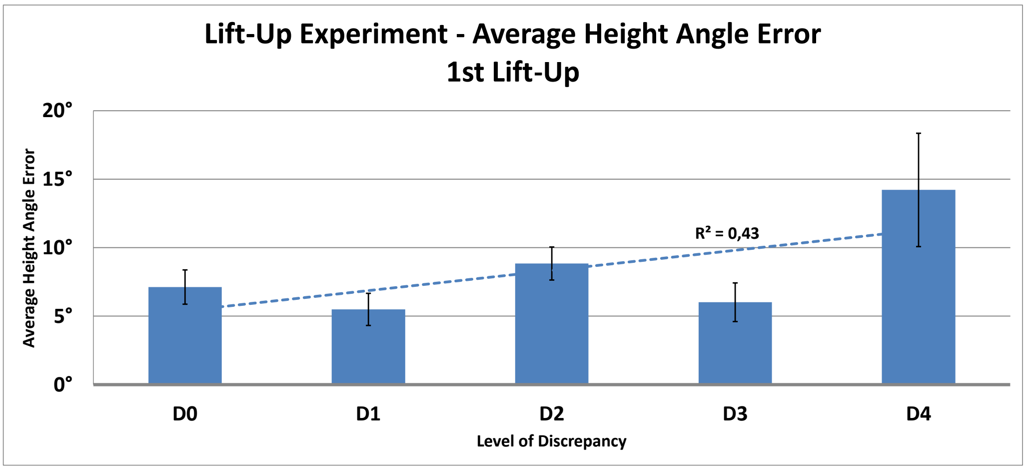

Figure 5.3: Average height angle errors in the first lift-up for the different levels of discrepancy in *Phase 2: Lift-Up* (P2) with 95% confidence intervals.

Test		T	p	Test		T	p
R1				V1			
$M = 2.00°, SD = 3.25°$				$M = -3.81°, SD = 2.58°$			
D	**E**	39	< 0.01	**C**	**F**	9	< 0.01
D	**F**	10	< 0.01	**C**	**I**	31	< 0.01
E	**F**	46	< 0.01	**F**	**I**	106	$= 0.21$
R2				V2			
$M = -0.98°, SD = 1.65°$				$M = -0.79°, SD = 2.50°$			
G	**H**	125	$= 0.50$	**B**	**E**	19	< 0.01
G	**I**	51	< 0.01	**B**	**H**	35	< 0.01
H	**I**	59	< 0.01	**E**	**H**	87	$= 0.08$
R3				V3			
$M = -4.63°, SD = 2.67°$				$M = 0.99°, SD = 2.80°$			
A	**B**	69	< 0.03	**A**	**D**	3	< 0.01
A	**C**	33	< 0.01	**A**	**G**	45	< 0.01
B	**C**	47	< 0.01	**D**	**G**	14	< 0.01

Table 5.3: Results of the pairwise Wilcoxon signed-rank tests (2-tailed) for varying visual (left) and haptic (right) stimuli. Here, the test statistic T and the p values are reported, with low values of T being required for significance. In all cases $N = 24$. Significances for $\alpha = 0.05$ are colored green.

Test		t	df	p
D0	**D1**	2.17	23	$= 0.041$
D0	**D2**	-2.55	23	$= 0.018$
D0	**D3**	2.16	23	$= 0.041$
D0	**D4**	-3.23	23	< 0.01
D1	**D2**	-5.35	23	< 0.01
D1	**D3**	-0.63	23	$= 0.536$
D1	**D4**	-4.27	23	< 0.01
D2	**D3**	3.59	23	< 0.01
D2	**D4**	-2.81	23	< 0.01
D3	**D4**	-3.65	23	< 0.01

Table 5.4: Results of the pairwise t-tests between the height angle errors in the first lift-up for different levels of discrepancy in *Phase 2: Lift-Up* (P2). Significances for $\alpha = 0.01$ are colored green.

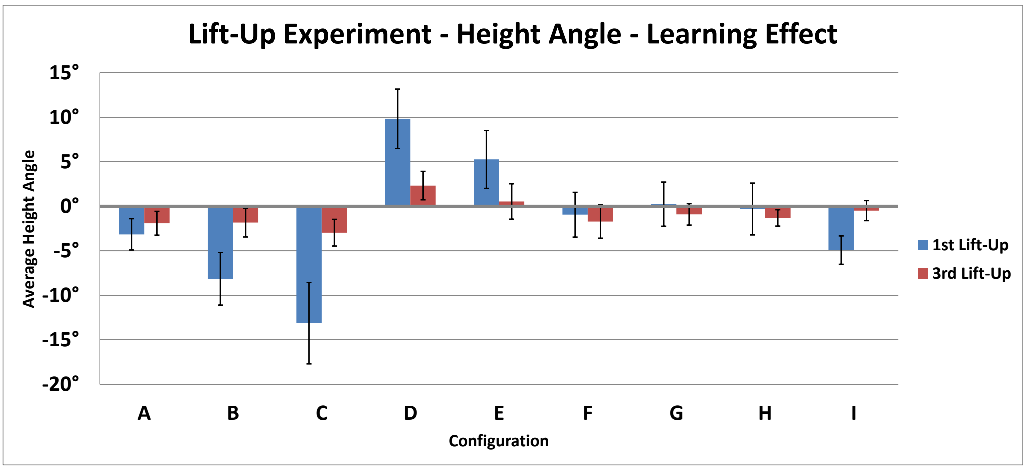

Figure 5.4: Average height angle in the first (blue) and third (red) repetition for each configuration in *Phase 2: Lift-Up* (P2) with 95% confidence intervals.

To investigate if learning effects within the three repetitions per configuration appeared, the error of the first lift-up and the third lift-up were compared. Figure 5.4 depicts the error, averaged over all 10 planes, of the first lift-up per configuration in blue and the corresponding average error of the third lift-up additionally in red. Pairwise t-tests between first and third lift-up were conducted to detect statistically significant improvements. The corresponding results are summarized in Table 5.5. It can be seen, that the error reduced to an almost constantly good level. The learning effect for the height angle error was proven to be statistically significant in configurations with large initial errors.

Con.	Dis.	$t(23)$	p
A	**D0**	-1.526	$= 0.14$
B	**D2**	-4.677	< 0.01
C	**D4**	-4.529	< 0.01
D	**D2**	4.528	< 0.01
E	**D0**	3.319	< 0.01
F	**D2**	0.569	$= 0.57$
G	**D1**	1.145	$= 0.26$
H	**D1**	0.393	$= 0.70$
I	**D3**	-4.443	< 0.01

Table 5.5: Results of the pairwise t-tests between the average height angle of the first and third lift-up repetition for each configuration in *Phase 2: Lift-Up* (P2).

Except from **E**, all of them were configurations with a discrepancy level of at least **D2**. In configurations for which no significant improvements could be shown, only small errors were made in the first place. Here, a detection of further statistically significant improvements with only 24 participants is hardly possible. Equivalent analysis (using Wilcoxon signed-rank tests) of the learning effect for the forward angle showed significant improvements only for **B** ($T = 34, p < 0.01$), **C** ($T = 58, p < 0.01$) and **I** ($T = 45, p < 0.01$). Hence one can summarize the results for both angles by stating that the learning effect was typically significant in configurations with larger levels of discrepancy: **D2** or above.

Angular Development across the Measurement Planes

To analyze the development of the angles across the 10 planes intersected during the lift-up process, univariate ANOVA tests were conducted with the independent variables *plane* and *configuration*. The results showed significances concerning the forward and height angle for the 10 different planes and 9 configurations (both: $p < 0.01$), with plane 1 as the bottom plane and plane 10 as the top plane. In most configurations, the error of the forward angle increased until plane 3, where the deflection was close to its maximum. Between plane 3 and 6, it could be observed that the participants started to correct their error which then decreased to zero. Above plane 6 the error distance of the forward angle increased in the opposite direction between plane 6 and 8 and finally decreased again to almost zero in average against plane 10. In general, the corresponding curves illustrated in Figure 5.5 (left) remind of a damped oscillation around zero. Interestingly, the smallest error could be found for all configurations in the range between plane 6 and 7, close to the area halfway between stand and double-target.
In contrast, Figure 5.5 (right) depicts the development of the height angle for all configurations across the planes. In most configurations, this error increased until plane 5. From then, the angle reduced towards plane 10.
For both the forward and height angle, the curves that differ most from this general behavior are **D** and **E**, which both have a balanced real distribution. A reason for that might be that in those configurations, no gravity-induced torques counteracted the forces exerted on the proxy by the user during lift-up.

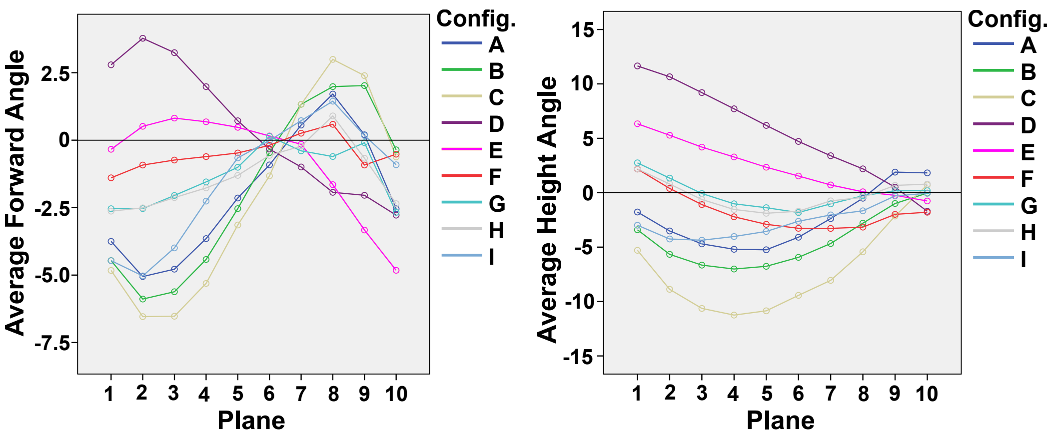

Figure 5.5: Development of the average forward (left) and height angle (right).

5.1.2 Subjective Feedback

After completing all three repetitions of a configuration in P2, the participants answered 7 post-task questions. The first two questions asked them to estimate the position of the CM *location* of the physical proxy in their hand and the virtual object they see. For this, 5 equidistant positions (1 = left, 2, 3 = center, 4, 5 = right) along the object were displayed. For the remaining questions, 6-point scales, similar to semantic differential scales, with anchors on the extremes, were used and displayed in the VE. These questions asked the participants to rate the perceived *realism*, i.e. the degree to which they thought to really hold the seen object in the hand, from 0 = "not at all" to 5 = "very strong". Moreover, participants were requested to rate the comfort of the object *handling* from 0 = "uncomfortable" to 5 = "comfortable" and the *mental* and *physical exertion* of the interaction from 0 = "not at all" to 5 = "very exhausting". Finally, participants were asked if there were any moments during the task, in which the behavior of the object surprised them or was unexpected and they were free to leave comments.

Center of Mass Estimation

Overall, the estimates of the CM locations were very good in all configurations. The results of the real and virtual CM location estimates (mean estimate value M with standard deviation SD) and the actual CM location (**CM**) for the relevant groups are summarized in Table 5.6. Wilcoxon signed-rank tests verified the differences between all groups to be statistically significant (with at least $p < 0.01$).

Group	**CM**	M	SD
R1	3	3.06	0.32
R2	4	4.47	0.39
R3	5	4.90	0.25
V1	1	1.08	0.28
V2	3	3.00	0.00
V3	5	4.94	0.16

Table 5.6: Results of the CM location estimates in *Phase 2: Lift-Up* (P2).

Realism & Handling

The average ratings of the perceived realism and the handling comfort are shown in Figure 5.6. Concerning the perceived realism, three configurations stand out: **A**, **E** and **G**. These are the configurations, in which the *direction* of the weight shift (*right* for **A** and **G**; *none* for **E**) match in the visual and haptic domain. The actual extent of the shift however might be completely different. A Wilcoxon signed-rank test comparing the group of matching directions (**A**, **E** and **G**) ($M = 4.50$, $SD = 0.57$) with the group of non-matching shift directions (all remaining configurations) ($M = 2.35$, $SD = 1.16$) proved the difference in the realism rating to be significant ($T = 0$, $p < 0.01$). Moreover, an analysis of the influence of weight

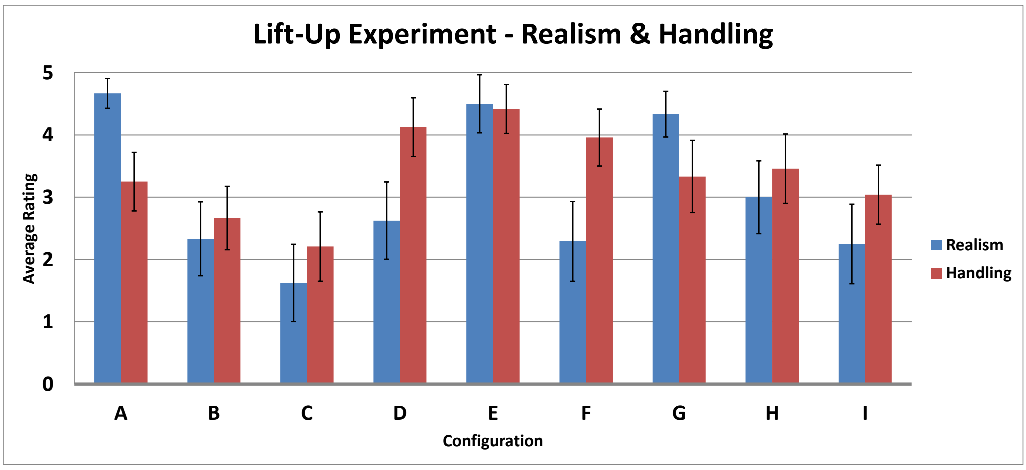

Figure 5.6: Average ratings of perceived realism (blue) and handling comfort (red) for each configuration in *Phase 2: Lift-Up* (P2) with 95% confidence intervals.

distribution discrepancy on the realism rating clearly shows the realism rating to decrease with increasing mismatch as can be seen in Figure 5.7. Except for the difference between **D2** and **D3**, pairwise Wilcoxon signed-rank tests showed all differences to be statistically significant for $\alpha = 0.05$. This influence of the discrepancy is also noticable when observing the "staircase" effect within the configurations of equal real weight distribution. As the discrepancy between **A**, **B** and **C** increases, so decreases the perceived realism. Similar effects can be seen between **D**, **E** and **F**, and **G**, **H** and **I**.

While the realism seems to primarily depend on the matching of real and virtual weight shift direction and the discrepancy, the rating of the handling comfort seems to be dependent primarily on the real weight distribution. As can be seen in Figure 5.6, the handling is rated most comfortable when the proxy object is balanced (R1 ($M = 4.17$, $SD = 0.80$)). A weak shift to the right in the haptic domain decreases the average rating slightly (R2 ($M = 3.28$, $SD = 1.07$)) and a strong shift worsens the handling even further (R3 ($M = 2.71$, $SD = 0.98$)). Pairwise Wilcoxon signed-rank tests showed these differences to be significant (with at least $p < 0.01$). When comparing again configurations of equivalent real weight distribution, a slight influence of the discrepancy can be noticed. An increase in discrepancy thus decreases the handling rating further (see the "staircase" patterns across R1, R2 and R3 in Figure 5.6) with a stronger influence in configurations with strong shifts. However, the decrease across different levels of discrepancy is less strong than for the realism rating, as can be seen in Figure 5.7. While most of the pairwise Wilcoxon signed-rank tests between the discrepancy levels showed significant differences for $\alpha = 0.05$, **D0** vs. **D2**, **D1** vs. **D2** and **D1** vs. **D3** did not yield significant results. Overall, the physical weight distribution seems to be the most decisive and contributing factor.

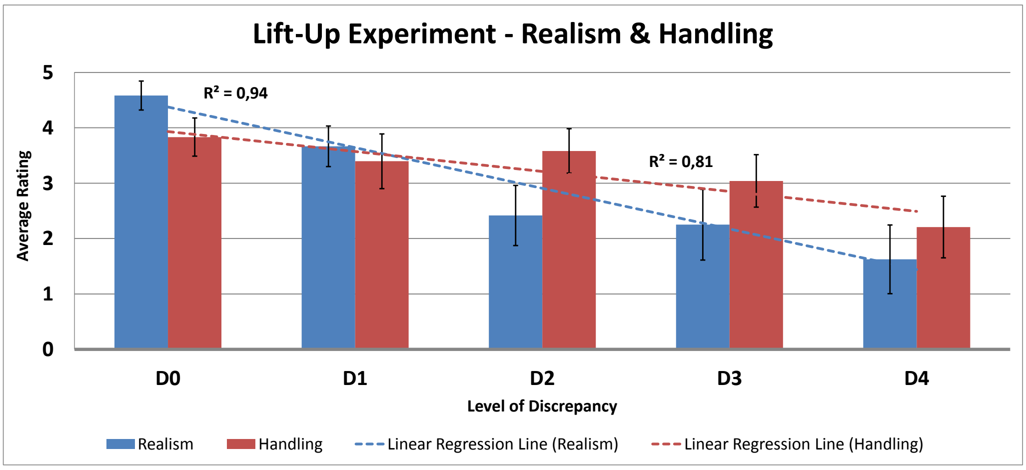

Figure 5.7: Average realism (blue) and handling (red) ratings for the different levels of discrepancy in *Phase 2: Lift-Up* (P2) with 95% confidence intervals, linear regression lines and coefficients of determination.

Physical Demand & Mental Demand

The physical and mental demand during the interaction was continuously rated low and relatively constant across all configurations. On the scale from 0 to 5, the average physical exertion was in the range between 1.04 and 1.84 for all configurations, thus the differences were minimal. Nevertheless, the real weight distribution could be shown to have a significant influence on the physical exertion. The average ratings of R1 ($M = 1.11$, $SD = 1.01$), R2 ($M = 1.39$, $SD = 1.11$) and R3 ($M = 1.79$, $SD = 1.23$) were all significantly different, as verified by pairwise Wilcoxon signed-rank tests (with at least $p < 0.01$). Similarly, the average mental exertion rating was in the range between 1.08 and 1.50 for all configurations. Again, differences were minimal and only the Wilcoxon signed-rank test between R1 ($M = 1.15$, $SD = 0.86$) and R3 ($M = 1.43$, $SD = 1.09$) showed a significant result ($T = 0$, $p < 0.02$) for $\alpha = 0.05$. All other differences could not be shown to be statistically significant.

Unexpected Object Behavior

Figure 5.8 illustrates the reports of unexpected or surprising object behavior during P2. When analyzing the chart, configuration **A** (4%), **E** (13%) and **G** (21%) immediately strike attention as here, significantly less reports of unexpected object behavior are recorded compared to all other configurations. Interestingly, this is the same group of configurations that stroke attention in the analysis of the perceived realism: the configurations in which the *direction* of the weight shift matched in the haptic and virtual domain. Thus when the physical and virtual weight distribution directions match, significantly less unexpected behavior was reported. On the other hand, as soon as the directions became inconsistent, the majority of participants (from 54% in **H** to 96% in **C**) reported unexpected object behavior. Moreover, an increase in the level of weight distribution discrepancy leads to an increase in the average number of reports of unexpected behavior, as can be seen in Figure 5.9.

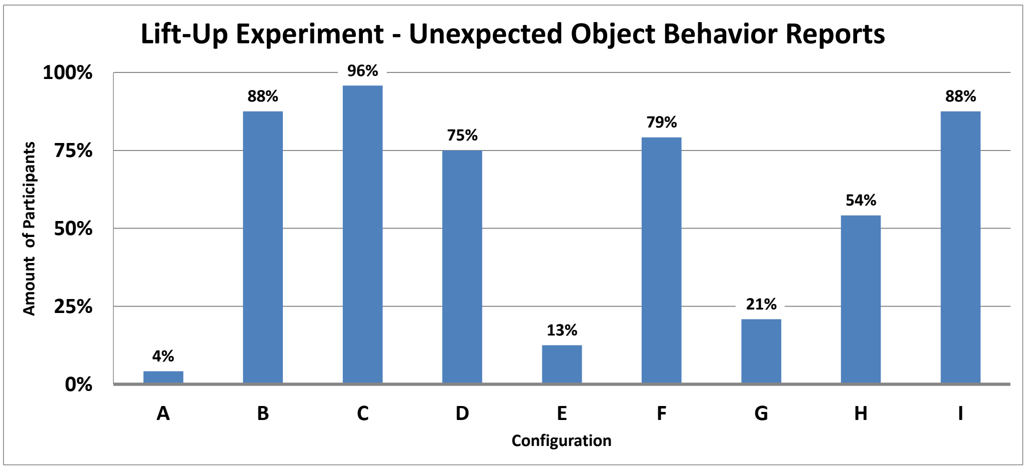

Figure 5.8: Percentage of participants reporting unexpected or surprising object behavior during the interaction in *Phase 2: Lift-Up* (P2).

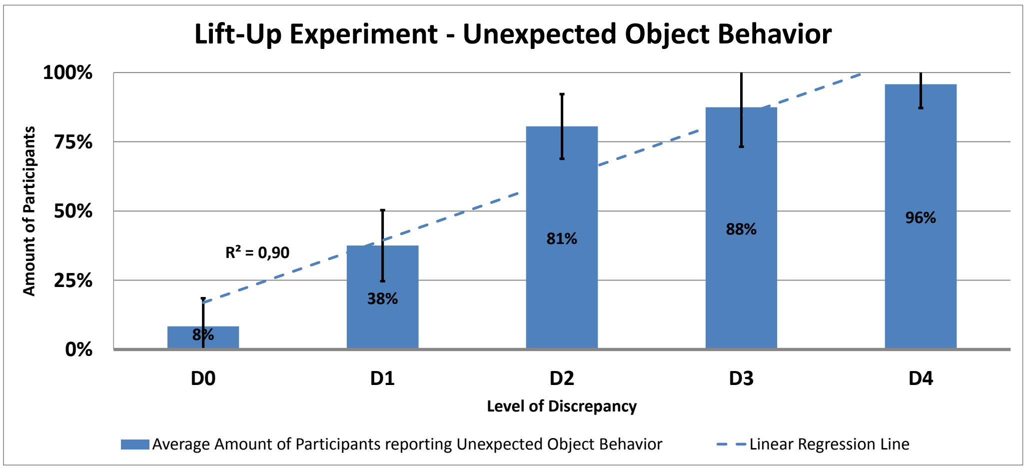

Figure 5.9: Average percentage of participants reporting unexpected object behavior for the different levels of discrepancy in *Phase 2: Lift-Up* (P2) with linear regression line, coefficient of determination and 95% confidence intervals.

5.2 Experiment 2: Length & Weight

This section summarizes the results of *Phase 3: Length* (P3) and *Phase 4: Weight* (P4) in the second experiment. As introduced, the participants' task in P3 was to implicitly state the perceived length and in P4 the perceived weight or heaviness of a virtual object by choosing one of three virtual wooden sticks in the VE. The choice should fall on the object that visually best matched the haptic impression of the grasped proxy object. The haptic impression changed between runs as the weight distribution of the proxy object was altered. For convenience, the selectable virtual objects were ordered by increasing length respectively weight and labeled from 1 to 3 on the cubes.

5.2.1 Length Perception

In *Phase 3: Length* (P3), participants had the choice between stick 1 (short; $0.5m$), stick 2 (medium; $1m$) and stick 3 (long; $2m$). In the course of P3, each participant encountered all three different weight distributions of the stick proxy (**S-R-G**, **S-R-M** and **S-R-T**) twice, which yielded 6 selections per participant. The reference impression for the selections matched stick 2 of medium length with the mid-shifted weight distribution (**S-R-M**).
For the analysis of the perceived length, the average value of the final selections of all participants, a value between 1 for *short* and 3 for *long*, was considered. Due to the order of the selection choices (ordered by increasing length), this average is a suitable indicator for the perceived object length. The results of P3 can be seen in Figure 5.10. The chart illustrates that the perceived length of the virtual object increased with the distance between the CM location and the point where the participant grasped the proxy. In other words, participants perceived the virtual object to be longer, the more the CM location shifted to the proxy's top end. On the contrary, participants perceived the object shorter, the more the weight distribution concentrated on the grip of the proxy. Pairwise Wilcoxon signed-rank tests proved the differences in the length perception of all three weight distributions to be statistically significant for $\alpha = 0.01$ (all with $p < 0.01$).

5.2.2 Weight Perception

Equivalent to P3, in *Phase 4: Weight* (P4), participants had the choice between stick 1 (light; $0.00015m^3$), stick 2 (moderate; $0.00045m^3$) and stick 3 (heavy; $0.00135m^3$). In the course of P4, each participant again encountered all three different weight distributions of the stick proxy (**S-R-G**, **S-R-M** and **S-R-T**) twice, which again yielded 6 selections per participant. The reference impression in P4 again matched stick 2 of moderate volume with the mid-shifted weight distribution (**S-R-M**).
For the analysis of the perceived weight or heaviness, the average of all participants' final selections, a value between 1 for *light* and 3 for *heavy*, was considered. Due to the order of the selection choices (ordered by increasing volume; or in

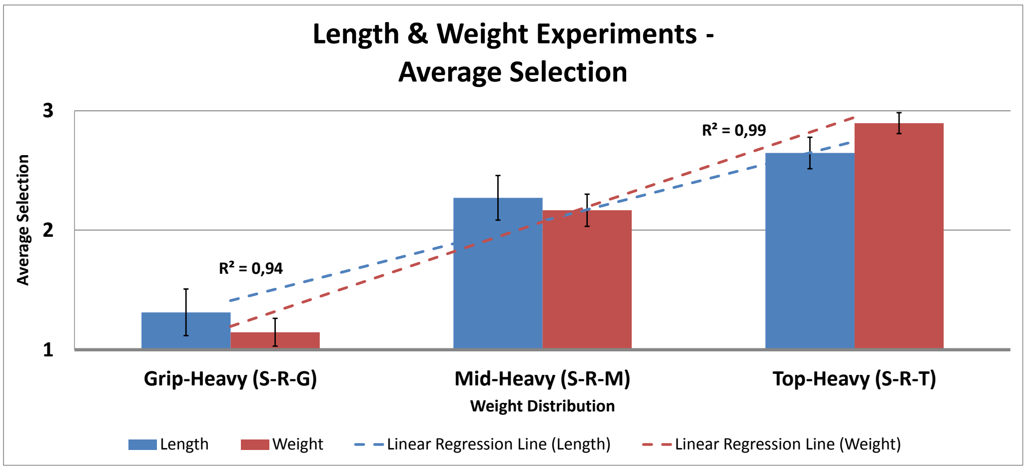

Figure 5.10: Average of the final selections for the proxy weight distributions in *Phase 3: Length* (P3) (blue) and *Phase 4: Weight* (P4) (red) with 95% confidence intervals, corresponding linear regression lines and coefficients of determination.

other words: increasing visually implied heaviness), this average is a suitable indicator for the perceived object weight. The results of P4 can be seen in Figure 5.10 as well. Similar to the results of the length perception, the perceived absolute weight or heaviness of the object increased with the distance between CM location and grasping point. In other words, participants perceived the virtual object to be heavier, the more the CM location was shifted towards the proxy's top end. On the contrary, participants perceived the object to be lighter, the more the weight distribution concentrated on the grip of the proxy. A comparison of the linear regression lines provides indication that the influence of weight distribution on perceived absolute weight is even stronger than on perceived length. As for the length perception, pairwise Wilcoxon signed-rank tests proved the differences in the weight perception of all three weight distributions to be statistically significant on a significance level of $\alpha = 0.01$ (all with $p < 0.01$).

5.3 SUS-Score & Post-Study Questionnaire

Upon completing all experiments, the participants were asked to fill out a SUS-Presence-Questionnaire and a concluding post-study questionnaire.

5.3.1 SUS-Score

As most of the participants were German speaking, the SUS questionnaire was translated to German. Care was taken during the translation process to come up with translations that preserve the original meaning of the questions so that the results are comparable to the original English version. The German version can be found in the appendix **SUS Presence Questionnaire: German Version**. The obtained SUS-scores were similar to those in the related literature. The average SUS-score ($M = 3.00$, $SD = 2.11$) of all participants was comparable to the SUS-score reported in Simeone et al.'s paper about SR [9] ($M = 2.50$, $SD = 1.91$).

5.3.2 Post-Study Questionnaire

In the final post-study questionnaire, the participants rated 8 aspects on a discrete scale from 0 to 5 with corresponding anchors. The results of all participants' ratings are summarized in the stacked bar chart in Figure 5.11.

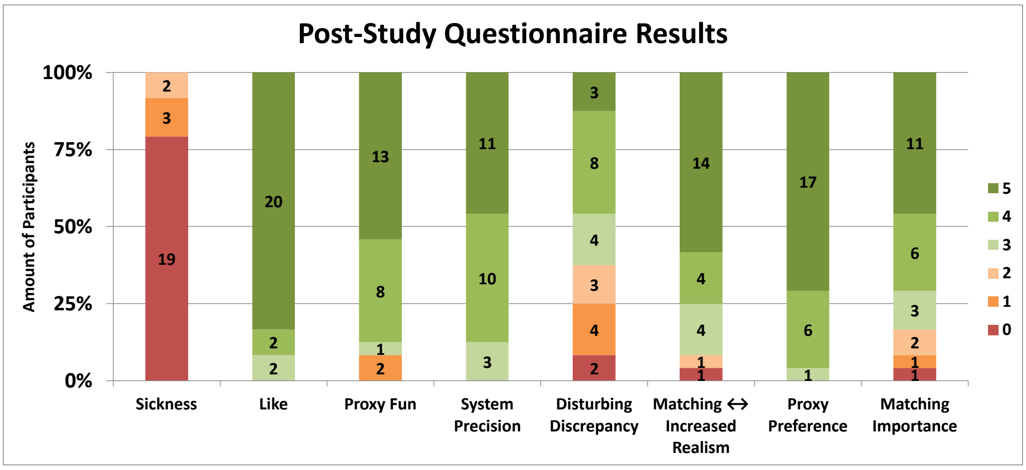

Figure 5.11: Stacked bar chart showing the amount of participants (y-axis) for each rating from 0 to 5 (color coded) for each post-study question (x-axis).

Post-Study Questions

The first question (**Sickness**) asked if any types of sickness problems were experienced during the experiments and if so, how severe they were. For this, participants rated on a scale from 0 = "no sickness problems" to 5 = "severe sickness problems". As the results show ($M = 0.29$, $SD = 0.62$), no noteworthy sickness problems arose. 19 of 24 participants did not feel any effects and the 5 reported issues were all related to slight and uncritical simulator sickness symptoms which were only reported after the comparably long experimental session. For the second question (**Like**), the participants rated how much they liked the VR experience from 0 = "not at all" to 5 = "very much". The results ($M = 4.75$, $SD = 0.61$) testifies that the interactive VR experience was very well-liked and participants enjoyed it.
Question three (**Proxy Fun**) asked for the fun the participants had with the physical interaction with the proxy object. The range went from 0 = "none" to 5 = "much". Very similar to the overall **Like** rating, the resonance was very positive ($M = 4.25$, $SD = 1.15$).

The fourth question (**Precision Rating**) asked for the participants' opinion regarding the precision of the VR system, especially regarding the interaction with the proxy. Participants could rate from 0 = "very imprecise" to 5 = "very precise". The overall score ($M = 4.33$, $SD = 0.70$) attested the developed system a very high precision.
Question five (**Disturbing Discrepancy**) asked the participants for how disturbing they rate a discrepancy in the weight distribution from 0 = "not disturbing at all" to 5 = "very disturbing". The results ($M = 2.88$, $SD = 1.57$) in this case were inconclusive. As can be seen in the chart, users strongly vary in how they perceive existing discrepancies: While 15 of them tended to rate them as disturbing in general, 9 of them did not generally find them disturbing.
In question six (**Matching $\leftrightarrow$ Increased Realism**), the participants could state if and how much they perceived the interaction to be more realistic when the weight distribution virtually and physically matched. The anchors here were 0 = "no increase in realism at all, it does not make a difference" to 5 = "yes, significantly more realistic". While the opinions regarding a weight distribution mismatch (**Disturbing Discrepancy**) were inconclusive across the participants, the results of this question ($M = 4.17$, $SD = 1.27$) however, testify a common opinion regarding matching weight distributions: The majority of participants stated that matching weight distributions increased their perceived realism.
The seventh question (**Proxy Preference**) asked the participant: "Assuming you have the choice, how likely would you choose a proxy (such as the ones used in the experiments) over a common input device (such as a controller, mouse or keyboard) for a VR game?". Possible answers were from 0 = "very unlikely" to 5 = "very likely". The obtained ratings ($M = 4.67$, $SD = 0.56$) reveal an overwhelming preference for proxy interaction with 17 out of 24 participants rating the probability as 5 = "very likely".
The last question (**Matching Importance**) directly asked the participants how important it would be for them, e.g. in a VR game, that the weight distribution of proxy objects matched the virtual objects' weight distribution. Ratings ranged from 0 = "unimportant" to 5 = "important". The average rating ($M = 3.87$, $SD = 1.42$) illustrates that the majority of users regards it as important.

Between-subject analyses were conducted with ANOVA tests for $\alpha = 0.05$ on the SUS-score and the post-study ratings (dependent variables) with regard to the VR experience, the experience with VR proxy interaction, the gaming experience and the sportiness of the participants (independent variables). The results verified a significant influence of the gaming experience on the SUS-score ($F = 3.967$, $p < 0.05$), the sickness rating ($F = 3.024$, $p < 0.05$) and the system precision rating ($F = 3.005$, $p < 0.05$). The results indicated that higher gaming experience led to slightly lower SUS-scores and lower sickness ratings. Novice and expert gamers rated the system precision as high, while casual gamers tended to rate it slightly lower. Concerning the VR experience, proxy experience and sportiness however, no significant influence could be substantiated.

Comments

In two concluding questions, participants were motivated to leave comments and to list VR applications which they think can be extended and improved in a meaningful way by means of proxy objects. The participants came up with a huge set of ideas which can be roughly categorized into 5 different categories: games, simulations, sports, movies and media in general. The simulation of all sorts of objects (weapons, tools, etc.) or units in various types of VR games was mentioned, as well as applications in map editors or ideas to simulate climbing movements. In addition to that, many different types of VR simulations in the fields of architecture, design, assembly, product presentation, medicine, training and aviation were named. Concerning sports, all sorts of stroke sports, shooting, fencing, boxing, archery, racing, billiard and sport lessons with virtual trainers in general were listed. Moreover, the idea of haptically enhanced VR movies came up as well as general ideas for pointing interactions in VR-UIs.
Besides that, the analysis of the comments brought up two interesting aspects that were both mentioned by several participants independently: The first is, that several participants in P3 had the impression that the weight of the physical object in their hand changed when the visual representation, i.e. the virtual object in their virtual hand, changed. More precisely, the same physical object was perceived heavier, when visually, a short object was displayed, and lighter, when a long stick was shown. Secondly, several participants reported to actually feel the proxy hit cubes made out of foam when in fact, only the virtual stick collided with the pure virtual selection cubes in P3 and P4. In addition to that, some participants reported the selection process in P3 to be slightly more difficult than in P4. Other comments again emphasized that mismatches in opposite directions were perceived as more disturbing than those involving a balanced object and that matching weight distributions are more comfortable. One participant added that weight distribution mismatches initially surprised him but after a short phase of familiarization, the discrepancy did no longer bother him. Finally, many participants used the comments to express again how much they enjoyed the experiment and the experience in general.

Chapter 6
Discussion

This chapter will focus on the discussion of the findings described in the previous chapter. The first section is concerned with the discussion and explanation of results obtained in *Experiment 1: Warm-Up & Lift-Up* (E1). In addition to that it will establish connections between the findings and the corresponding hypotheses formulated for the first experiment. Subsequently, the second section will do the same for the findings of *Experiment 2: Length & Weight* (E2). The third section will then be concerned with the SUS-score and the post-study questions. Eventually, the last section will bring the most important discoveries together to conclude the chapter by discussing their general implications.

6.1 Experiment 1: Warm-Up & Lift-Up

The first experiment was designed to serve the **first goal** of this thesis: the investigation of the influence of proxy *weight distribution* on VR user interaction and behavior. For this, a set of hypotheses (**H1.1**, **H1.2**, **H1.3** and **H1.4**) was formulated in chapter **Experiments**, section **Experiment 1: Warm-Up & Lift-Up**. The following discussion will establish connections between supporting results and hypotheses.

6.1.1 Forward Angle & Height Angle

The angular measurements and their analysis provide insights into the consequences of the interaction with imbalanced proxy objects. In addition, the role of visual-haptic weight distribution mismatches is investigated. The analysis of the angular measurements in E1 is discussed in the following.

Forward Angle

The results of the forward angle show that the proxy's real weight distribution has a significant influence on the user's interaction with the object. The measurements indicate that when the CM location is shifted away from the grasping point, e.g. strongly towards the right end, the user automatically pulls the heavier end closer to the body. As the CM location moves away from the user's hand, the lever arm and thus the induced torque increases. Consequently, the user has to counteract stronger forces and by pulling the CM closer to the body, the general lever is decreased slightly and the user improves his control over the object. Although a tendency is indicated by the corresponding chart, it could not be shown that the difference between the forward angle of the *half-right* shift and the *right* shift is statistically significant. On the other hand, significant differences between the forward angle for the balanced object and both right shifted objects could be verified. This is a first support for **H1.1**, which states that the *direction* of the weight distribution has more impact on VR proxy interaction than the absolute extent of the shift.

Height Angle

The analysis of the height angle could prove a significant influence of both the virtual and real weight distribution on user behavior and VR proxy interaction in general. The characteristic "staircase" pattern[10] that can be observed in the charts of the average height angle and the corresponding tests verified the importance of both the virtual and real weight distribution independently:
When for example the haptic stimulus, i.e. the weight distribution of the proxy, is fixed, interactions with objects of different visual stimuli, i.e. weight distributions of the virtual object, yield significantly different errors. Vice versa, the same holds for a fixed visual stimulus and varying haptic stimuli. When the user perceives the same virtual weight distribution, interactions with different weight distributions in the proxy yield significantly different height angle errors.
An explanation for this is, that the user plans the interaction (and therewith applied forces, grasping points, etc.) before lifting the object up. These applied forces are planned based on the knowledge about the object and its visual appearance. When the user is not familiar with an object, he primarily relies on its visual appearance. If now a weight distribution discrepancy is present, the interaction with the proxy is planned based on misleading assumptions credited to the virtual object's visual appearance. Practically speaking, "wrong" forces might be applied to the "wrong" side of the proxy when e.g. the weights of the proxy and the virtual object are shifted to opposite sides. Configuration **C** is a perfect example for that. Here the virtual object is a dumbbell with the weight

[10] The "staircase" pattern is the step-wise increase or decrease in the measurements of the height angle among configurations of the same real or virtual weight distribution. This pattern can e.g. clearly be seen for configurations **A**, **B** and **C** (all with the real weight distribution **D-R-R**) or the configurations **D**, **E** and **F** (all with the real weight distribution **D-R-C**) in Figure 5.2.

shifted strongly to the left end. The proxy object however has a weight distribution that is strongly shifted to the right end. As a consequence, the users pulls the left end of the object more strongly upwards, led by the visual stimulus, which only increases the proxy object roll to the right induced by gravity. This might then in turn affect the user as he is surprised to encounter unexpected object behavior. Such unexpected object behavior entails the risk of breaks in immersion, unwanted errors and even the risk of hurting oneself or others and damaging the environment or the proxy. The surprising effect is especially intense in early phases of the interaction with virtual objects, e.g. when picking up an object in a SR. However, with increasing familiarization and when facing explicit tasks to be accomplished with the object, a learning effect could be verified. The comparison of the first and third lift-up showed the participants to compensate for the weight distribution mismatches quickly. Errors could be reduced to an almost constantly good level for the height angle. Similar improvements could also be shown for the forward angle in some configurations. Observations in the **Pilot Study** confirmed these results. Led by the visual input, e.g. a slightly rolled object, participants compensate for the errors in order to fulfill a task. Depending on the concentration level, this compensation might even happen without the user explicitly noticing it.

Finally, the explicit investigation of the discrepancy showed that the average height angle error increases with increasing levels of weight distribution mismatch. This verifies **H1.2** and in general shows that weight distribution as a proxy property does have a significant influence on user behavior and VR proxy interaction. Matching weight distributions yield significantly less errors regarding unwanted object roll and the user's control over the object, especially when unfamiliar, was shown to depend on the direction of the real and virtual weight distribution, the extent of the shifts and the corresponding level of discrepancy.

Angular Development across the Measurement Planes

Concerning the user's compensation, the analysis of the forward and height angles' development across the 10 measurement planes brought up interesting insights. As the results of the forward angle show, the user's first reaction after lifting up a *right* shifted proxy was to pull the right end slightly towards the body. Directly upon that, around plane 3, the user seems to counteract this reaction in order to reduce the error but overshoots slightly against plane 8. After this, a further correction again reduces the error as the proxy approaches the double-target. This alternation of compensation and slight overshooting results in an oscillating curve of the average forward angle across the planes. It is noteworthy that due to this alternating behavior, the average forward angle of all configurations approached the zero value around plane 6 and 7 which lies almost halfway between proxy stand and double-target.

In contrast, the development of the height angle differs substantially from the development of the forward angle. When lifting up a *right* shifted proxy, the

average height angle error typically increased, with the height angle becoming increasingly negative, towards plane 5 halfway between stand and double-target. From then on it decreased towards the double-target due to compensation. Here, no oscillation or overshooting can be observed. The direction of the roll indicated by the sign of the height angle was generally determined by the real weight distribution and the mismatch, thus by the configuration. Except for **F**, **G** and **H**, the direction of the roll did not change across the planes. Instead only the extent of the object roll differed.
The only configurations that differed from the presented behaviors in some cases were configurations with a balanced proxy or very low levels of discrepancy. This can be explained by the fact that correction forces were planned and applied while no or only weak forces from no or weak weight shifts counteracted. This then resulted in different developments of the angles across the planes.

6.1.2 Subjective Feedback

Besides the objective measures, subjective feedback of the participants gave crucial insights into the effect the proxy's weight distribution has on the user's impression. In the post-task questions, subjective feedback regarding CM location estimates, perceived realism, handling comfort, mental and physical demand and reports of unexpected behavior were gathered.

Center of Mass Estimation

The results of the real and virtual CM location estimation tasks showed, that participants were mostly able to correctly estimate virtual and real CM locations. Apart from the estimation of the real *half-right* shift, which was slightly more difficult with some participants dithering between the *half-right* and *right* CM location, the estimation of all other real and virtual locations were mostly correct. Participants were able to assess the direction of weight shifts perfectly. The proven significances verify, that the participants were able to precisely recognize the shift direction and more or less correctly the specific CM locations of the virtual and real objects. Thus they were aware of existing real-virtual weight distribution discrepancies. The fact, that the assessment of the shift direction seems easier for users than the estimation of the specific CM location, can also be seen as a support for **H1.1**.

Realism & Handling

Concerning the perceived realism, the obtained ratings draw a clear picture of the most influential factors:
The primary factor that most dominantly influences the perceived realism is the *direction* of the weight shift. If the directions of the real and virtual weight shift match, the perceived realism is very high and significantly better than for

non-matching shift directions, which further supports **H1.1**. The *extent* of the shift then only plays a secondary role. The obtained results show, that the difference in the perceived realism between configurations with matching shift directions and non-matching shift extents, and configurations with both matching directions and extents, are negligible. While matching extents might further increase the realism, the results indicate that this is no necessity for a highly realistic experience as matching shift directions suffice.
If however the shift directions differ, severe drops in the perceived realism ratings occur. The deciding factor for the perceived realism then is the level of weight distribution discrepancy. The results show that the perceived realism and therewith the believability of the illusion decreases with increasing mismatch, which verifies the first part of **H1.3**.

A similar clear picture can be drawn regarding the handling comfort. As for the perceived realism, the most influential factors can be extracted from the results: The primary factor for the handling comfort is the balancedness of the proxy. A clear trend can be observed: The closer the proxy's CM location is to the grasping point, i.e. the smaller the physical lever arm is, the more comfortable is the handling. An additional secondary factor is the weight distribution discrepancy. Although it is not as influential as for the perceived realism, an increase of the mismatch still leads to a decrease in the rating of the handling, which completes the verification of **H1.3**. Furthermore, the comparison of the drop from configuration **A** to **C** with the drop from **E** to **F** or **G** to **I** indicates mismatches to gain importance with increasingly strong weight shifts.

Physical Demand & Mental Demand

The feedback regarding physical and mental demand showed the interaction with the introduced proxy objects to be suitable for most users. The exertion ratings were overall very low. The most important influence seems to come from the weight distribution of the proxy object. Although rated low in this experiment, the interaction with increasingly imbalanced objects also slightly increases the demand physically and mentally, as the statistical significance tests showed. This is in compliance with observations of the **Pilot Study**. As here, the Warm-Up game was played for a longer time, some participants reported the interaction with heavily imbalanced objects to be significantly more exertive than the interaction with balanced or only slightly weight shifted proxies.

Unexpected Object Behavior

The last post-task measures are the reports of unexpected object behavior. As already mentioned, surprising object behavior during interaction comes with the risk of breaks in immersion, confusion of the user or even damage to the environment due to unplanned movements of the proxy. Because of that, it can

be regarded as an important measure when investigating proxy properties. The results unambiguously show that the reports of unexpected object behavior are related to the realism rating:
The primary and most decisive factor is the *direction* of the weight shift. If the shift direction of the virtual object and the proxy match, the amount of users experiencing unexpected object behavior during interaction is very low. The secondary factor here again seems to be the extent of the shift. A match in direction and extent of the shift yields least reports (4% for **A**) , a mismatch in only the extent slightly increases the amount (21% for **G**). However, the results are still significantly better than in configurations with inconsistent shift directions. These findings thus further support **H1.1**.
When a directional mismatch is present, the majority of the participants experiences unexpected behavior even for low levels of discrepancy (**D1**). An increasing mismatch worsens this issue further until almost all users experience it (with 96% of the participants reporting it for **D4**).
These findings verify the final hypothesis **H1.4** of E1 and further emphasize the importance of considering the weight distribution of objects involved in VR proxy interaction.

6.2 Experiment 2: Length & Weight

The **second goal** was approached by *Experiment 2: Length & Weight* (E2). Concerning the weight distribution's influence on the user's perception of virtual objects, two hypotheses (**H2.1** and **H2.2**) were formulated in chapter **Experiments**, section **Experiment 2: Length & Weight**, which are discussed in the following.

Length & Weight Perception

The significant differences in the length and weight perception for different proxy weight distributions found in the length (P3) and weight (P4) experiments verify **H2.1** and **H2.2**. They prove, that despite a fixed *absolute weight* and *length* of the proxy, the *perceived length* and the *perceived absolute weight* or *heaviness* of a virtual object can be controlled by the proxy's weight distribution.
By shifting mass and therewith the CM location away from the user's grasping point at the bottom end of a rod-shaped proxy, the moment of inertia and the lever arm is increased. The increase in the moment of inertia changes the "rotational resistance" of the proxy object and the shift of the CM location outwards increases the torque at the grasping point. The haptic perception of both effects in conjunction with the perception of an appropriate visual representation eventually controls the perceived length and weight of the virtual object. The increase in the object's inertia and the increased torque that is to be counteracted, induced by the leverage effect due to gravity and an increased lever arm, in conjunction with the display of an increased length, makes the user really believe to interact with a longer virtual object. The effect can also be used in conjunction with the display

of an increasingly heavy object. Equivalently, the increase in the felt inertia and the increase in the forces to be counteracted with the wrist, make the user believe to interact with an heavier virtual object.
These results on the one hand verify findings by Turvey [60] and Chan [59] on the perception of non-visible rods. But the investigation in this thesis went one step further by bringing these results from perceptual sciences to the VR domain. E2 can be seen as a proof-of-concept that demonstrates first, that the results not only hold for *non-visible* rod perception, but also for the perception of virtual objects that are *visible* in the VE while haptic stimuli originating from different proxy objects are perceived. Secondly, the experiments demonstrate one way to use these results in a meaningful way to enhance VR experiences.
Possible applications for this technique to simulate virtual object length and weight can be found in most VR application areas. Interactive stick- or rod-shaped objects like weapons, tools, etc. held at one end, are for example frequently found in games and simulations. Here, the findings could directly be applied.

6.3 SUS-Score & Post-Study Questionnaire

The post-study results and their analysis give insights into the suitability of the experiment, the general acceptance of VR proxy interaction and the importance of a proxy's weight distribution. The corresponding findings are discussed in the following.

6.3.1 SUS-Score

With an average SUS-score comparable to scores in the related literature, an adequate average level of immersion is certified. Feedback of the participants suggests that the immersion during E2 was slightly higher than in E1, which might be due to the more detailed and realistic environment. The significant influence of the gaming experience on the SUS-score agrees with findings in Usoh's paper [55]. Both this effect and the decrease in the sickness rating of frequent gamers can be explained by their increased experience with computer generated 3D environments, practice and them being used to the very high visual and auditory quality of modern games.
The fact that no significant influence of VR experience, experience with proxy interaction and sportiness could be detected further emphasizes that the introduced concepts are suitable for most types of users. Users experienced in VR proxy interaction or very sporty users can use the system and enjoy the experience as much as users without any experience or not very sporty users.

6.3.2 Post-Study Questionnaire

General feedback in a post-study questionnaire helps to understand the participants' experience. The questionnaire used here gave the participants the opportunity to provide feedback on the most important factors involved in the VR experiment. By analyzing their concluding comments, new insights into the perception of the participants could be gained.

Post-Study Questions

With the ratings for **Like**, **Proxy Fun** and **Proxy Preference** being very good, one can conclude that VR proxy interaction in general, as well as the developed proxies in particular, are accepted and favored by users. Moreover the interaction with proxy objects whose weight distributions matches the virtual object's weight distribution was generally rated as important and users testified that it increases the realism significantly. It is noteworthy that the perception of weight distribution mismatches is inconclusive across participants. Some find it disturbing while others do not. However, the conclusive feedback regarding matching distributions suggests to take the weight distribution of objects into consideration when designing proxies. The high system precision ratings and the absence of sickness problems verified the developed VR system to be suitable for the experimental investigation.

Comments

The participants' comments brought up some interesting ideas for applications of proxy objects and some classical areas of application were named as well. Regarding weight distribution discrepancies, some participants stated that when they fully concentrated on a task, they got used to mismatches quickly and they found themselves unconsciously compensating for them. This indicates that smaller mismatches might remain unnoticed given appropriate tasks and that immersion plays a central role in the perception of virtual objects.
Also related to immersion might be the observation of users feeling collisions with the virtual cubes. An explanation for that might be that, when due to the integration of haptics, a high level of immersion is reached, the human brain might prepare muscles and tendons in the arm and wrist for an imminent impact. In the course of that, muscles may unconsciously contract although no physical impact occurs. This might eventually be surprising to the user which might consequently get the impression of a collision with a light and soft material.
The second observation, i.e. some users' impression of a change in the proxy's physical weight when a change in the visual representation occurred, can probably be explained by the so called *size-weight illusion*. In the *size-weight illusion*, people perceive a large object, with the same mass as a smaller object, as lighter, and the smaller object as heavier [60, 62].

6.4 Implications

The investigation of the *weight distribution*'s influence on user behavior (**Goal 1**) and perception (**Goal 2**) established it as a crucial proxy property. For interactive VR experiences with high degrees of immersion and realism, the weight distribution of virtual objects and their physical representatives must be taken into account to reduce unwanted errors during interaction, to prevent breaks in immersion due to unexpected object behavior and to increase the perceived realism. In addition to that, the second experiment could demonstrate that the weight distribution of a proxy has great potential to be used as a kind of "tool" to simulate different proxy properties. It could be shown that the proxy weight distribution can be used to simulate different object lengths and weights believably. This is a contribution to the goal of making more generic proxies able to believably simulate numerous different virtual objects.

6.4.1 Proxy Design Guidelines

From these findings, a set of proxy design guidelines can be deduced:

1. **Level:** Proxy objects should be built in a way that allows to configure slight weight shifts into different directions. This increases realism and generality and allows to believably simulate objects of different weight distributions.
2. **Level:** In addition to slight shifts into different directions (**1. Level**), proxies should be built in a way that also allows to vary the extent of these shifts. By this, realism is increased further, the simulation becomes even more authentic and a fine-grained simulation of weight distribution details becomes possible. Moreover, this allows for the simulation of different object properties like length and weight.
3. **Level:** Proxy objects should use actuators, controlled by the computer system simulating the VE, to change the proxy weight distribution's direction (**1. Level**) and extent (**2. Level**) fully automatically. The proxy could then be reclassified as a hybrid haptics device.

6.4.2 Key Considerations

These guidelines are based on the following considerations:
To increase realism and generality, a proxy object should be able to shift its CM location slightly into different directions (**1. Level**). By this, it could realistically simulate various objects of different weight distributions. As the shift direction was shown to be more important for the perception than the shift extent and because matching shift directions increase realism significantly (**H1.1**, **H1.3**), for simple proxy designs, it may suffice to offer a few distinct shift directions. By this, real-virtual mismatches might be decreased enough to prevent severe errors

during interaction (**H1.2**) and to allow for improved handling (**H1.3**). Moreover, when using only gentle shifts, the problem of too uncomfortable handling is of no concern anyway, as small shifts will typically exert less strong forces than exact replicas. Simultaneously, the risk of users experiencing unexpected object behavior is decreased significantly (**H1.1**, **H1.4**), compared to objects not taking into account shift direction matches. Concerning practicability, such slight shifts could already be implemented in small proxy objects. With regard to existing designs, one could also think of CM shifting extension modules that could flexibly be attached to existing proxies.
For applications that require more flexibility, objects that, in addition to the direction, also control the extent of weight shifts can be imagined (**2. Level**). These proxies could then simulate virtual objects in a more detailed fashion and would offer increased flexibility. In addition to the simulation of differently weight shifted objects, they could simulate various different proxy properties such as virtual object length (**H2.1**) and heaviness (**H2.2**). This further enhances generality crucially. By this, proxy properties that physically can only be modified with great effort or that are even impossible to modify on the fly, are simulated by translating masses along the proxy. Changing the length of a proxy object at runtime, for example, is difficult and impractical. Changing its absolute weight requires even more sophisticated approaches or may even be impossible while preserving ungroundedness and flexibility. Thus, a proxy object or game controller that simulates all this by electromechanically translating parts of its mass to shift its CM would be an elegant solution (**3. Level**).

Put together, the guidelines presented here motivate the construction and use of CM location shifting proxy objects for VR applications. Generic proxy objects could be built, that make use of actuators to displace masses in order to shift the proxy's CM location. These objects would then combine aspects of passive haptics and active haptics and could thus be classified as hybrid haptic devices.

6.4.3 Summary

In summary, the investigation could shed light onto the importance of weight distribution as a proxy property and its influence on user behavior during VR interaction (**Goal 1-a**). Moreover, the role of directional weight shift (**Goal 1-b**) and visual-haptic stimuli discrepancies became more clear. The second experiment could clarify the influence of weight distribution on perceived object form (in particular: length) (**Goal 2-a**) and perceived object weight (**Goal 2-b**). In conjunction with the subjective measures of both experiments, the influence of proxy weight distribution on user perception in VRs in general was investigated.

As mentioned in the **Related Work** chapter, one goal of this thesis is to extend the knowledge about proxy properties and their influence on VR proxy interaction. Summarizing the findings of this thesis, one can now extend Table 2.1 by an additional row outlined in Table 6.1.

Proxy Properties - State of Research
Additional Row

Property	Results	Reference
Weight Distribution	• mismatch affects errors during interaction significantly • learning effect can reduce errors during interaction • shift direction is more important than shift extent • matching shift direction primary factor for realism • matching shift direction primary factor for risk of unexpected object behavior • physical proxy weight distribution primary factor for handling comfort • decreasing mismatch increases handling comfort • decreasing mismatch increases realism • decreasing mismatch decreases risk of unexpected object behavior • can be used to control perceived object length • can be used to control perceived object weight	this thesis

Table 6.1: Additional row extending Table 2.1 on the state of research on proxy properties by the findings of this thesis about proxy weight distribution.

Chapter 7
Conclusion and Outlook

The last chapter concludes the thesis and provides a brief summary of the conducted research and the findings. Eventually, some recommendations for future work are provided.

7.1 Conclusion

The following sections provide a brief conclusion of this work. The major goals, the motivation and the experimental concepts are summarized. Moreover, the most important findings are stated together with the implications derived from them.

7.1.1 Goals

The goal of this thesis was to investigate a property of VR proxy objects that so far was left understudied: the *weight distribution*. The aim was to investigate the weight distribution's influence on the user's behavior during VR proxy interaction and to find out more about the role of directional shift and visual-haptic discrepancies. Moreover, the effect on the user's perception of virtual objects should be studied.

7.1.2 Motivation & Experimental Design

A detailed overview over the related literature summarized the state of research regarding active haptics, passive haptics and mixed approaches. Here, the lack of investigation concerning weight distribution as a distinct proxy property was clearly noticeable and motivated this work. An experimental approach was chosen for the investigation and various concepts for experiments and studies, environments and physical proxies were developed. First results from a pilot study motivated a refinement of the experimental concept in several iterations and finally, a user study concept comprising two subsequent experiments was worked out. The first experiment studied the influence of weight distribution and related visual-haptic discrepancies on errors during interaction and on the user's general perception of the objects interacted with. The second experiment investigated the potential of the weight distribution to simulate different proxy properties like perceived object length and weight. For the lab-based experiments, an interactive VR system was designed and implemented that allowed to experience immersive VEs. By integrating a motion capturing system, users were able to interact with objects in the VE by means of proxy interaction. Complementary, a special proxy design was developed that allowed to build rod-shaped proxies whose weight distribution can be changed effortlessly by replugging differently weighted chambers. Based on this concept, two types of proxies were built. The dumbbell proxy used in the first experiment haptically represented a virtual dumbbell and the stick proxy was the physical substitution for differently shaped wooden sticks in the second experiment.

7.1.3 Findings

The main study was conducted with 24 participants. The results and the detailed analysis showed proxy weight distribution and especially mismatches between real and virtual objects to have a significant influence on errors made during interaction. Unwanted object roll angles and the risk of users experiencing unexpected object behavior during interaction were found to increase with increasing weight distribution mismatch, especially when the object is unfamiliar. Likewise, perceived realism and handling comfort were shown to decrease as weight distribution discrepancies became greater. Directional weight shift was found to be the primary factor influencing perceived realism and the risk of experiencing unexpected object behavior. In general, the results indicated in various ways that the direction of weight shifts is more important than the absolute shift extent for various factors involved in VR proxy interaction. When familiarity with the object increased and the user concentrated on a task, however, users could quickly compensate for unwanted errors using the visual input. This was verified by the learning effect observed in the first experiment.
The second experiment could in addition illustrate the great potential of variable shift extents. It was shown that the extent of proxy weight shifts in a certain direction can be used to simulate virtual objects of different lengths and absolute weights by controlling the distance between the CM location and the user's hand grasping the proxy. By displacing masses, the proxy's moment of inertia and lever arm were increased or decreased. The haptic perception of this in conjunction with the visual perception of differently shaped virtual objects was shown to control the user's perception of virtual objects and their sense of realism.

7.1.4 Implications

From these findings, a set of proxy design guidelines was deduced, which promote three increasingly sophisticated levels of including weight distribution in proxy design. The most basic integration is to include slight weight shifts in different directions. A more detailed simulation of weight distribution, virtual object length and weight is possible when implementing shifts of varying extent and in the optimal case, all this is automated using computer controlled actuators.

In summary, the findings of this thesis fill a gap in the research on proxy properties and can help to develop generic proxies and immersive VR applications.

The research presented in this thesis has been submitted in form of a research paper to the *ACM Conference on Human Factors in Computing Systems (CHI) 2016*.

7.2 Recommendations for Future Work

Based on the findings of this thesis, it would be interesting to further investigate the influence of weight distribution on other factors involved in VR proxy interaction, for example on interaction accuracy. Moreover, future work in this area could try to derive formulas that describe the simulation of perceived length and weight of virtual objects more precisely. This would help designers and developers to derive the weight shifts necessary to simulate desired object lengths and weights. In addition to that, it would be exciting to research whether further proxy properties can be simulated by means of weight shifts and if actuators can simulate collision forces or wind and fluid resistance effects using weight distribution changes. As the investigation in this thesis was primarily concerned with rod-shaped proxies and similar virtual objects, future work should investigate non-rod-shaped objects too.

Inspired by redirection techniques for walking, it would be interesting to investigate the feasibility of VR redirection techniques that redirect the user's hand interacting with a virtual object. Here, weight shifts could potentially be used to steer the user's movement and to navigate his hand in order to avoid collisions with the environment.

Apart from that, future research should continue to investigate further proxy properties and their influence on VR proxy interaction.

As a next step, it is planned to build a weight-shifting VR proxy object that can change its weight distribution automatically, controlled by the VR system, to further investigate its potential for VR proxy interaction.

Appendix A
Virtual Dumbbell Design

A.1 Concept

The virtual dumbbells used in the experiments were designed and modeled in a way, so that their CM location was located at the desired positions, i.e. at the center or offset by $20cm$ to one end. Although a virtual object does not have a physical weight nor a physical weight distribution, the dumbbells were designed so that, if physically build, their CM would be at exactly the desired location relative to the center of the dumbbell. For this, some simplifying assumptions were made and the appropriate radius r of the weight disk attached to the dumbbell in the shifted state was derived. This physically-based approach to the virtual object design ensured that participants could correctly assess the CM location of the virtual object visually. Moreover it allowed to argue about the virtual dumbbell's CM location and mismatches to the proxy's CM.

A.2 Design

A.2.1 Overview

The following sketch illustrates the virtual dumbbell in its imbalanced state. Here, the CM location is offset by $20cm$ to the right. The physically-based design abstracts away from small object details such as the wooden balls used to hit the targets or the symmetric handle with the diameter of the real proxy object at the center. Ignoring such features, the design comes down to a combination of two basic symmetric objects: a rod and a disk.

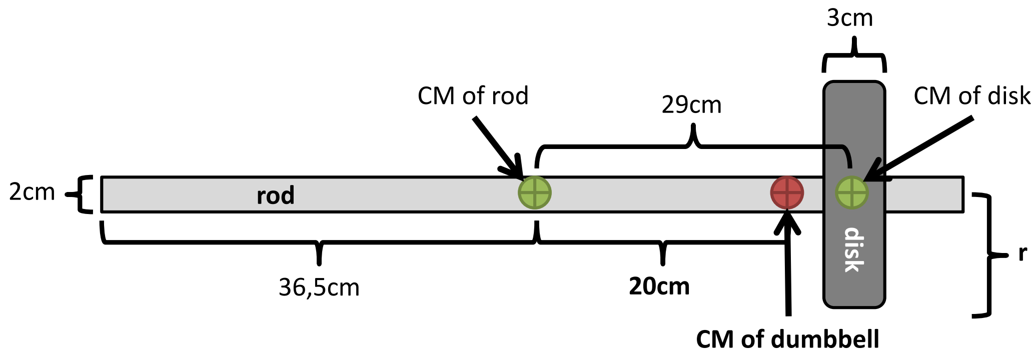

Figure A.1: Sketch of the rod and the disk that make up the virtual dumbbell with the CM shifted by $20cm$ to the right. The sketch is not true to scale.

A.2.2 Assumptions

A set of assumptions was made concerning the dumbbell's form and material:

- **Assumption 1:** The rod has a radius $r_{rod} = 0.01m = 1cm$ and a length of $h_{rod} = 0.73m = 73cm$
- **Assumption 2:** The weight disks are always attached $0.29m = 29cm$ away from the center of the rod and they are $h_{disk} = 0.03m = 3cm$ thick.
- **Assumption 3:** The rod and the disks are made of the same material with constant density ρ.

The desired CM offset of the virtual dumbbell is $CM = 0.2m = 20cm$ towards the heavy end.

Under these assumptions, the remaining unknown variable to be found is the radius r of the disk. This radius is derived in the following.

A.2.3 Derivation of the Disk Radius

As the rod and the disk are symmetric objects, their CMs are located at their center and thus along the dumbbell's main axis. As the dumbbell's CM is located between the rod's and the disk's CM, it is located along this axis as well. Thus only the linear offset along this axis must be considered. With the origin being at the center of the rod, the exact location of the rod's and the disk's CM are known to be at:

- $CM_{rod} = 0m$
- $CM_{disk} = 0.29m$

The dumbbell's CM is thus located at:

$$CM = \frac{m_{rod} \cdot CM_{rod} + m_{disk} \cdot CM_{disk}}{m_{rod} + m_{disk}}$$

With the volumes V_{rod} and V_{disk} of the rod and disk, the masses can be written as:

$$m_{rod} = \rho \cdot V_{rod}$$
$$m_{disk} = \rho \cdot V_{disk}$$

Assuming constant density ρ, the material cancels out and we get:

$$\begin{aligned}
CM &= \frac{\rho \cdot (V_{rod} \cdot CM_{rod} + V_{disk} \cdot CM_{disk})}{\rho \cdot (V_{rod} + V_{disk})} \\
&= \frac{V_{rod} \cdot CM_{rod} + V_{disk} \cdot CM_{disk}}{V_{rod} + V_{disk}} \\
&= \frac{V_{disk} \cdot CM_{disk}}{V_{rod} + V_{disk}} \\
&= \frac{V_{disk} \cdot CM_{disk}}{V_{disk} \cdot (\frac{1}{V_{disk}} \cdot V_{rod} + 1)} \\
&= \frac{CM_{disk}}{\frac{V_{rod}}{V_{disk}} + 1}
\end{aligned}$$

$$\begin{aligned}
\Leftrightarrow \quad & CM \cdot (\frac{V_{rod}}{V_{disk}} + 1) = CM_{disk} \\
\Leftrightarrow \quad & \frac{V_{rod}}{V_{disk}} + 1 = \frac{CM_{disk}}{CM} \\
\Leftrightarrow \quad & \frac{V_{rod}}{V_{disk}} = \frac{CM_{disk}}{CM} - 1 \\
\Leftrightarrow \quad & \frac{1}{V_{disk}} = \frac{CM_{disk} - CM}{CM \cdot V_{rod}} \\
\Leftrightarrow \quad & V_{disk} = \frac{CM \cdot V_{rod}}{CM_{disk} - CM}
\end{aligned}$$

As the thickness of the disk $h_{disk} = 0.03m$ and the shape of the rod is known, we can write:

$$V_{disk} = \pi \cdot r^2 \cdot h_{disk} - V_{intersect} = \pi \cdot r^2 \cdot 0.03m - V_{intersect}$$
$$V_{rod} = \pi \cdot r_{rod}^2 \cdot h_{rod} = \pi \cdot (0.01m)^2 \cdot 0.73m = 0.00023m^3$$

with r being the radius of the disk to compute and $V_{intersect}$ being the intersection volume of the rod and the disk. This intersection volume is:

$$V_{intersect} = \pi \cdot r_{rod}^2 \cdot h_{disk} = \pi \cdot (0.01m)^2 \cdot 0.03m$$

With this, the radius r can finally be derived:

$$\begin{aligned}
\Rightarrow \quad V_{disk} &= \frac{CM \cdot V_{rod}}{CM_{disk} - CM} \\
&= \frac{0.2m \cdot 0.00023m^3}{0.29m - 0.2m} \\
&= 0.00051m^3 \\
&= \pi \cdot r^2 \cdot h_{disk} - V_{intersect} \\
\Rightarrow \quad r^2 &= \frac{V_{disk} + V_{intersect}}{\pi \cdot h_{disk}} \\
\Rightarrow \quad r &= \sqrt{\frac{V_{disk} + V_{intersect}}{\pi \cdot h_{disk}}} \\
&= \sqrt{\frac{0.00051m^3 + \pi \cdot (0.01m)^2 \cdot 0.03m}{\pi \cdot 0.03m}} \\
&= 0.0742m = 7.42cm \approx 7.5cm
\end{aligned}$$

Thus with a disk radius of $r \approx 7.5cm$, the CM of the dumbbell object is shifted $20cm$ towards the heavy end.
The balanced dumbbell was designed accordingly. Two disks were fixed on it at $29cm$ left and right of its center and so its CM was located exactly in the middle. For the balanced virtual dumbbell, the disks' radii were scaled appropriately, so that $V_{disk_l} = V_{disk_r} = \frac{V_{disk}}{2}$. This ensured that both the balanced and imbalanced dumbbells had exactly the same total weight and moment of inertia.

Appendix B

SUS Presence Questionnaire: German Version

1. Bitte bewerten Sie auf einer Skala von 1 bis 7, wie sehr Sie das Gefühl hatten, *in* der virtuellen Umgebung zu sein, wobei 7 Ihr normales Gefühl ist, an einem Ort zu sein.

   Ich hatte das Gefühl tatsächlich *in* der virtuellen Umgebung zu sein

	1	2	3	4	5	6	7	
gar nicht	□	□	□	□	□	□	□	**sehr**

2. Inwieweit gab es Momente während des Spiels, in denen die virtuelle Umgebung die Realität für Sie war?

   Es gab Momente während des Spiels, in welchen die virtuelle Umgebung die Realität für mich war

	1	2	3	4	5	6	7	
niemals	□	□	□	□	□	□	□	**fast durchgehend**

3. Wenn Sie an die Virtual Reality Erfahrung zurück denken, erinnern Sie sich dann an die virtuelle Umgebung eher wie an Bilder, die Sie einmal gesehen haben, oder eher wie an Orte, an denen Sie einmal gewesen sind?

   An die virtuelle Umgebung erinnere ich mich eher wie an

	1	2	3	4	5	6	7	
Bilder, die ich gesehen habe	☐	☐	☐	☐	☐	☐	☐	**Orte, an denen ich war**

4. Welches Gefühl war während Sie das Spiel gespielt haben insgesamt am stärksten: das Gefühl *in* der virtuellen Umgebung zu sein oder das Gefühl in einem Labor zu stehen und an einem Experiment teilzunehmen?

   Ich hatte eher das Gefühl ... zu sein

	1	2	3	4	5	6	7	
in einem Labor, nicht *in* der virtuellen Umgebung	☐	☐	☐	☐	☐	☐	☐	***in* der virtuellen Umgebung**

5. Denken Sie an Ihre Zeit in der virtuellen Umgebung. Wie "struktur-ähnlich" sind Ihre Erinnerungen daran im Vergleich zu Erinnerungen an andere Orte, an denen Sie heute waren?

   Mit "struktur-ähnlich" ist gemeint, inwiefern Sie visuelle Erinnerungen an die virtuelle Umgebung haben, ob diese Erinnerungen in Farbe sind, inwiefern die Erinnerungen lebendig und realistisch sind, die Länge und Stärke der Erinnerungen, die imaginäre Vorstellung der virtuellen Orte, wie panoramaartig die Erinnerungen sind usw.

   Meine Erinnerungen an die virtuelle Umgebung als einen Ort sind ähnlich zu den Erinnerungen an reale Orte, an denen ich heute war

	1	2	3	4	5	6	7	
gar nicht	☐	☐	☐	☐	☐	☐	☐	**sehr**

6. Dachten Sie während Ihrer Zeit in der virtuellen Umgebung oft selbst, dass Sie sich tatsächlich in der virtuellen Umgebung befinden?

   Während meiner Zeit in der virtuellen Umgebung dachte ich oft, ich stände tatsächlich in der virtuellen Umgebung

	1	2	3	4	5	6	7	
nicht sehr oft	☐	☐	☐	☐	☐	☐	☐	**sehr oft**

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List of Abbreviations

2D
: *Two-Dimensional*

3D
: *Three-Dimensional*

AR
: *Augmented Reality*

AV
: *Augmented Virtuality*

CG
: *Computer Graphics*

CH
: *Computer Haptics*

CM
: *Center of Mass*

CSV
: *Comma Separated Values*

D-R-C
: ***Dumbbell** Proxy - **Real** Weight Distribution - **Center***

D-R-HR
: ***Dumbbell** Proxy - **Real** Weight Distribution - **Half-Right** Shifted*

D-R-R
: ***Dumbbell** Proxy - **Real** Weight Distribution - **Right** Shifted*

D-V-C
: ***Dumbbell** Proxy - **Virtual** Weight Distribution - **Center***

D-V-L
: ***Dumbbell*** *Proxy -* ***Virtual*** *Weight Distribution -* ***Left*** *Shifted*

D-V-R
: ***Dumbbell*** *Proxy -* ***Virtual*** *Weight Distribution -* ***Right*** *Shifted*

D0
: *Real-Virtual Weight Distribution Discrepancy Level 0 -* 0cm

D1
: *Real-Virtual Weight Distribution Discrepancy Level 1 -* 10cm

D2
: *Real-Virtual Weight Distribution Discrepancy Level 2 -* 20cm

D3
: *Real-Virtual Weight Distribution Discrepancy Level 3 -* 30cm

D4
: *Real-Virtual Weight Distribution Discrepancy Level 4 -* 40cm

E1
: *Experiment 1: Warm-Up & Lift-Up*

E2
: *Experiment 2: Length & Weight*

EWK
: *Extend of World Knowledge*

HIP
: *Haptic Interface Point*

HMD
: *Head Mounted Display*

MR
: *Mixed Reality*

P1
: *Phase 1: Warm-Up*

P2
: *Phase 2: Lift-Up*

P3
: *Phase 3: Length*

P4
: *Phase 4: Weight*

PVC
: *Polyvinyl chloride*

RE
: *Real Environment*

RV
: *Reality-Virtuality*

S-R-G
: ***Stick** Proxy - **Real** Weight Distribution - **Grip**-Heavy*

S-R-M
: ***Stick** Proxy - **Real** Weight Distribution - **Mid**-Heavy*

S-R-T
: ***Stick** Proxy - **Real** Weight Distribution - **Top**-Heavy*

SR
: *Substitutional Reality*

UI
: *User Interface*

VE
: *Virtual Environment*

VR
: *Virtual Reality*

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