Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality

André Zenner and Antonio Krüger

Fig. 1. A user interacting with *Shifty* in our experimental setup. *Shifty* is a rod-shaped dynamic passive haptic proxy that can change its internal weight distribution to automatically adapt its passive haptic feedback. *Shifty* can be used to enhance the perception of virtual objects and provides a compelling and dynamic passive haptic feedback.

Abstract—We define the concept of *Dynamic Passive Haptic Feedback* (DPHF) for virtual reality by introducing the weight-shifting physical DPHF proxy object *Shifty*. This concept combines actuators known from active haptics and physical proxies known from passive haptics to construct proxies that automatically adapt their passive haptic feedback. We describe the concept behind our ungrounded weight-shifting DPHF proxy *Shifty* and the implementation of our prototype. We then investigate how *Shifty* can, by automatically changing its internal weight distribution, enhance the user's perception of virtual objects interacted with in two experiments. In a first experiment, we show that *Shifty* can enhance the perception of virtual objects changing in shape, especially in length and thickness. Here, *Shifty* was shown to increase the user's fun and perceived realism significantly, compared to an equivalent passive haptic proxy. In a second experiment, *Shifty* is used to pick up virtual objects of different virtual weights. The results show that *Shifty* enhances the perception of weight and thus the perceived realism by adapting its kinesthetic feedback to the picked-up virtual object. In the same experiment, we additionally show that specific combinations of haptic, visual and auditory feedback during the pick-up interaction help to compensate for visual-haptic mismatch perceived during the shifting process.

Index Terms—Dynamic passive haptic feedback, input devices, virtual reality, haptics, perception

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1 INTRODUCTION

Haptic feedback is known to be one of the next big challenges for immersive virtual reality (VR). This paper introduces a new class of haptic feedback that mixes aspects of *Active Haptic Feedback* and *Passive Haptic Feedback* called *Dynamic Passive Haptic Feedback* (DPHF). With DPHF we combine the strengths of passive haptic proxy objects and active haptic systems. As an example we introduce the novel rod-shaped DPHF proxy *Shifty*. It is an ungrounded generic physical proxy that uses actuators to slowly shift an internal weight, changing its passive haptic properties in order to enhance the perception of objects during VR interaction.

When interacting in our daily life, we constantly perceive haptic cues that help us understand an object's physical properties such as its shape, weight, weight distribution, temperature and texture. This is essential for a safe, precise and effective interaction with an object. While sophisticated haptic feedback systems were developed in the past, the systems that come with major VR consumer devices, primarily targeting gaming and education, still use relatively simple controller devices, especially in terms of the kinesthetic feedback provided. Prominent examples are the controllers of the *HTC Vive* [1] or the *Oculus Rift* [2]. These controllers are passive haptic proxy objects that physically represent virtual objects. The realism of their feedback, however, is limited. Equipped with small vibration motors, a set of feedback effects varying in vibration strength and frequency can be achieved. While this can produce very compelling effects for some interactions in the virtual environment (VE), such as tensing a bowstring or pulling a lever, a major drawback is the fact that the kinesthetic properties always remain unchanged. For most interactions like picking up a virtual object with the controller, or holding an object that changes its form or material, users expect different haptic sensations before and after the event. A common problem related to this is the balloon-like feeling of virtual objects: as each picked-up object feels the same with respect to its inertia, picking up larger objects becomes unrealistic as they feel much too lightweight.

With *Shifty* we introduce a novel physical proxy to solve these issues by enhancing the perception of virtual objects users interact with. *Shifty* can, without exerting noticeable active forces, slowly change its kinesthetic feedback automatically during runtime by shifting a weight along its main axis to change its rotational inertia. The user then gets

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- *André Zenner, German Research Center for Artificial Intelligence (DFKI) Saarland Informatics Campus. E-mail: andre.zenner@dfki.de.*
- *Antonio Krüger, German Research Center for Artificial Intelligence (DFKI) Saarland Informatics Campus. E-mail: krueger@dfki.de.*

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[1] www.htcvive.com

[2] www.oculus.com/touch

the impression of feeling objects of different weights or forms. In two evaluating experiments we show how *Shifty* can enhance object perception in VR.

In the remainder of this paper, we will review some important results of related work and introduce the concept behind *Shifty* and the implementation of the prototype. Following up, both experimental user studies are described and we present and discuss the results. Then the paper is concluded and ideas for future research are presented.

2 RELATED WORK

This section provides an overview on different approaches to VR haptics and classifies our approach in the Reality-Virtuality continuum. We further present previous investigations on proxy object properties and their influence on the VR experience before we introduce related devices and concepts.

2.1 Reality-Virtuality Continuum

Milgram and Colquhoun [21] introduced the Reality-Virtuality continuum, an important taxonomy that classifies systems based on their real and virtual aspects. The continuum spans two major poles: *Reality* and *Virtuality*. Every system between those poles, i.e. that combines inputs of both the real and virtual world in some dimension, is classified as *Mixed Reality*. Although originally referring to visual input only, today, additional dimensions such as haptics and audio are taken into account as well. In this continuous space of Mixed Reality systems, we further distinguish between *Augmented Reality* and *Augmented Virtuality*. While the stimuli perceived by the user in augmented reality originate primarily from reality, the primary stimulation in augmented virtuality systems is purely virtual. Jeon and Choi [15] extended this continuum to a two-dimensional composite continuum of vision and haptic.

Regarding Milgram and Colquhoun's taxonomy, a VR setup as considered in this paper is classified as *augmented virtuality*. In Jeon and Choi's continuum, it can be classified as *visual virtuality - haptic mixed reality*. The content primarily perceived by the user is purely virtual (the visual and most of the auditory channel), while the haptic perception when interacting with the physical proxy is reality-based combining passive props with actuators. Following the Reality-Virtuality continuum of Milgram and Colquhoun, in Sect. 4.3 of this paper we will define the Active-Passive Haptics continuum.

2.2 Haptic Feedback

There exist several different approaches to haptics in the context of VR. In general, one can distinguish between *Active Haptic Feedback* (abbreviated as AHF in the remainder of the paper) and *Passive Haptic Feedback* (abbreviated as PHF in the remainder of the paper). Besides these, there also exist mixed approaches and approaches based on PHF that exploit the visual dominance to intensify the haptic impression.

2.2.1 Active Haptic Feedback (AHF)

Active haptic interfaces use computer controlled actuators to actively exert forces on the user of the VR system and thereby provide a haptic stimulation. Prominent examples are the *PHANToM* [19] haptic interface device or the *Moog HapticMaster* [30]. Like many active haptic devices, these are grounded machines that offer an actuated end-effector touched by the user. These devices are often large and expensive, and are unsuitable for many setups. Besides these grounded devices, more lightweight ungrounded solutions exist as well. Some of them, for example GyroTab [3], offer a reactive torque feedback utilizing the gyro effect. Others are glove- or exoskeleton-based systems like the *Rutgers Master II - New Design* [4] or the *CyberGrasp* [6]. In addition to active force feedback systems, more subtle vibro-tactile feedback systems as used in the *CyberTouch* [6] glove, or electro-tactile feedback systems, also exist [10]. Concepts that simulate force feedback by means of ungrounded tactile feedback were recently presented as well. Their form-factor is similar to that of already-existing VR controllers and sliding plates are used to produce a skin-stretching feedback in the hand [22], e.g. simulating the effect of weapon recoil.

The major advantage of AHF is the great generality offered by these solutions, as they promise to deliver a great variety of haptic sensations with a single device. However, a common drawback of AHF devices, whether grounded or ungrounded, is their mechanical and computational complexity. Sophisticated haptic rendering algorithms must be used to correctly compute collision forces, friction and texture details. To deliver the desired feedback, relatively complex mechanics must be controlled precisely and at high update rates. In addition, active haptic devices are often safety-critical as failures may harm the user.

2.2.2 Passive Haptic Feedback (PHF)

In contrast to AHF, passive haptic approaches do not use any computer controlled actuators to exert forces on the user. Concepts like the *Elastic-Arm* [1] use rubber bands fixed on the user's wrist and shoulder to produce passive haptic force feedback when the band stretches as the user's arm reaches out. Aside from that, passive haptic exoskeleton systems such as the *Dexmo* [8] were recently introduced. Here, the movement of the fingers can be blocked when collisions in the virtual space occur. The user thus perceives passive haptic feedback from the exoskeleton's blocking mechanics when touching rigid virtual objects, instead of forces actively being exerted on him. As the blocking mechanics adapt the passive haptic feedback in this concept, *Dexmo* also fulfills our definition of DPHF that we will introduce in Sect. 3. However, in most VR systems employing PHF, users interact with physical props, i.e. real objects that physically represent virtual counterparts or implement a tangible user interface. The proxies are typically low-fidelity objects made out of cheap and available materials [11]. A very lightweight example is the rolled sheet of paper used as a tubular prop in Jackson et al.'s tangible visualization interface for thin fiber structures [13]. When representing touchable virtual objects, the proxies are spatially registered with their virtual counterpart. As users touch the proxies, they are provided with natural haptic feedback defined by the proxy's physical structure. In most cases, though, the proxy is not an exact replication of the virtual object and thus, a certain mismatch between proxy and object in the VE exists. This mismatch may affect various dimensions such as shape, weight, size, temperature, texture, function or weight distribution. Past research has investigated the influence of these object properties and corresponding mismatches on object perception and interactions in VEs [16, 18, 24, 32, 33]. It was found that all of them may affect the perceived realism and the user's immersion. However, the sensitivity of humans toward mismatches in these dimensions varies from dimension to dimension. The results on the influence of weight distribution are summarized in the following section about human perception in VR.

As opposed to AHF, passive haptics profit from being very low-cost and in general much less complex. Low-fidelity proxy objects are typically easy, cheap and fast to assemble, either by manual prototyping or using a 3D printer. Moreover, a physical proxy can provide natural and rich haptic feedback at no further computational cost. The major drawback of PHF approaches is their lack of generality. Certain degrees of mismatch in different physical dimensions between virtual and real objects can be accepted without significantly influencing immersion. However, the set of virtual objects that can be represented realistically by a conventional passive proxy is limited.

2.2.3 Mixed & Alternative Approaches to Haptic Feedback

Besides AHF and PHF, mixed and alternative approaches exist. Mixed approaches to haptics involve both passive and active haptic components. A prominent example is the concept of *encounter-type haptics* or *Robotic Graphics* [20, 28]. Here, robotic actuators display physical proxies at different locations in a just-in-time manner by changing their position and orientation, to allow the user to physically touch objects in the VE. However, mixed haptic concepts are also known from non-VR contexts. The shape-changing Morphees [23] for example use actuating elements to change the shape of mobile devices.

Other alternatives make use of the strong visual stimulation in VR setups. Kohli [17] introduced a haptic distortion technique that exploits the effect of visual dominance to add generality to proxy objects. By visually distorting the surface of a virtual object and the space around it, the technique can be used to make users perceive a single proxy object as differently shaped objects.

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The concept of *Pseudo Haptics* exploits the visual dominance effect as well. Here, users typically interact with some physical prop and while this prop does not change, the control-display ratio or other aspects of the visual representation are modified to simulate physical properties of the object such as weight or friction [7,14]. This technique can also be used in augmented reality contexts [12]. By increasing the speed of a moved proxy in virtual space, users perceive the object as lighter, while decreasing the virtual speed makes users perceive the object as heavier. The *Virtual Mitten* [2] interaction paradigm is an example of a mix of PHF and pseudo haptics. Here, users hold a physical object equipped with springs to grasp virtual objects and pseudo haptics are used to make users perceive different levels of effort.

2.3 Human Perception

Very important for the development of *Shifty* are results on the weight distribution's influence on the perception of objects in VR. Past perceptual research by Chan [5] and Turvey [29] has shown that the perceived length and weight of non-visible rods wielded in reality is directly related to the rod's moment of inertia. A recent investigation of the weight distribution's influence on VR proxy interaction [32] could show that this effect still holds in VEs with visible virtual rods. By testing a set of discrete weight distributions with increasing moments of inertia, convincing passive haptic feedback for virtual objects of different lengths and weights could be produced. Additionally, it was shown that mismatches in the object's weight distribution can increase error rates and the risk of experiencing unexpected object behavior which impairs immersion. From these results one can derive that proxy objects should ideally mimic the virtual object's weight distribution. However, the results also indicate that the direction of the shift is of primary importance for a user's perceived realism and that the absolute strength of the proxy's weight shift must not necessarily match the virtual object's. Perceived realism can already be increased by shifting the proxy's weight in the same direction as the virtual object's, and small shifts already suffice for immersive experiences. Concerning the perception of length, an interesting non-VR experiment by Yao and Hayward [31] showed a different way to make the user perceive different rod lengths. By haptically simulating the rumbling vibration feedback of a small object rolling along the inner cavity of a wielded tube and its impact at the end, the perceived length of the tube could be manipulated. However, the experiment did not involve any weight shifts and the participants anticipated a change in the weight distribution of the tube as they were observed to compensate for a higher torque, when the virtual inner object was presumed to be at the end of the tube.

2.4 Weight-Shifting Objects

Concepts involving weight-shifting objects are known from various different areas of interaction research. One example is the *TorqueBAR* [27]. It is a two-handed device held in both hands horizontally with a total weight of slightly more than $1000g$. It can linearly displace the center of mass from left to right and vice versa to provide inertial kinesthetic force feedback. More lightweight weight-shifting objects are discussed in the field of mobile devices. Equipping smartphones or other mobiles with weight-shifting ability has been investigated for example by Hemmert et al. [9]. There also exist modern haptic devices designed for use in large-scale VR entertainment systems. Among them is the *Arena Infinity v1* by *StrikerVR* [26], a VR gun controller that aims to simulate the haptic sensation of weapon recoil based on repulsion feedback and linear actuators.

3 DYNAMIC PASSIVE HAPTIC FEEDBACK (DPHF)

The concept of *Dynamic Passive Haptic Feedback* (DPHF) aims to reduce the lack of generality of passive haptic proxy objects, devices and environments: We propose to equip passive haptic proxies, devices and environments with actuating elements known from active haptic systems to build *hybrids that use actuators to change their passive haptic properties (e.g. size, shape, weight, weight distribution, texture, temperature, position, orientation, function, etc.), without exerting noticeable active forces on the user.*

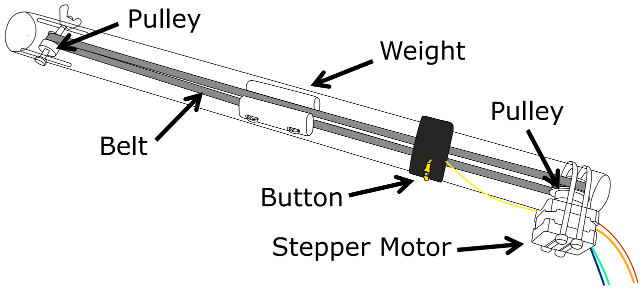

Fig. 2. Concept sketch of *Shifty* with its main components.

Shifty fulfills this definition and is thus a DPHF proxy. Besides *Shifty*, the *Dexmo* [8] fulfills this definition as well and can thus be classified as a DPHF exoskeleton device. When used as VR proxies, shape changing objects like the Morphees [23] could be classified as DPHF objects as well and implementations of robotic graphics [20,28] can be imagined that fulfill the definition of DPHF environments.

4 CONCEPT & IMPLEMENTATION OF SHIFTY

In the following, we introduce our DPHF proxy object *Shifty*. We first outline the general concept before we describe the implementation of our prototype.

4.1 Concept

Shifty is designed as a rod-shaped VR proxy object or VR controller. In contrast to traditional passive haptic proxies, *Shifty* can alter its physical properties through an actuating motor, controlled by the VR system to haptically represent a large set of different virtual objects. The user holds *Shifty* with one hand at the grip end and by continuously shifting an internal weight between the grip and top end, it can translate its center of mass and change its rotational inertia. Equipped with a pushbutton, *Shifty* allows the user to interact with the VE. This makes *Shifty* suitable for interactions supported by modern VR controllers. One of the most relevant thereof is the ability to pick up other virtual objects by pushing and holding the trigger button on the device.

4.1.1 Effects

Shifting an internal weight towards the top of the object and thus away from the rotational axes passing through the user's wrist increases the rotational resistance. This does not change the proxy's absolute weight, but the user has to apply stronger forces to move the object. With *Shifty*, we leverage this effect and claim that the slow and continuous change in *Shifty*'s rotational inertia can, synchronized with appropriate visual and auditory feedback, change the user's perception of the linked virtual object. More specifically, we claim that by continuously increasing the moment of inertia, users believably perceive the linked virtual object as becoming heavier, thicker or longer, depending on the visual feedback. Conversely, by decreasing the moment of inertia, the virtual object is perceived as becoming lighter, shorter or thinner. We further claim that the realism perceived by the user can be increased significantly by changing the rotational inertia when picking up virtual objects. These claims are investigated in two experimental evaluations.

4.1.2 Construction

Mechanically, *Shifty* consists of a lightweight body and remotely controlled internal mechanics that linearly displace a mass along this body. The position of the weight is defined as $p \in [0,1]$ where $p = 0$ means the weight is at the grip end and $p = 1$ means it is located at the top end of the proxy. Grasping the proxy at the grip end with one hand, the user can use a pushbutton beneath the index finger to trigger actions in the VE. Fig. 2 shows a concept sketch.

To be compatible with large-scale VR systems and redirection techniques [25] in which users can walk around through large tracking areas, *Shifty* was designed to be mobile. In our first prototype, the power supply and controlling electronics are all built into a small backpack and

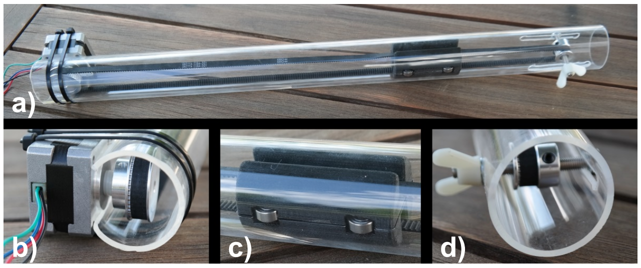

Fig. 3. Our prototype implementation of *Shifty*: a) the assembled proxy without the button and the rigid-body target, b) the NEMA-14 type stepper motor and the grip end pulley with the belt, c) the 3D printed internal weight filled with lead and the bearings, d) the top end pulley.

the actual proxy is connected to this backpack via cables. The cable length allows for unrestricted arm movement. *Shifty* communicates wirelessly with the VR system.

4.2 Implementation

In the following, we present the hardware and software implementation of our *Shifty* prototype.

4.2.1 Hardware

After several trials and with our prior knowledge we have decided to build the prototype of *Shifty* as described in the following. A lightweight plexiglass pipe (length = 505 *mm*, wall thickness = 2 *mm*, diameter = 40 *mm*) is used for the body and a cheap and lightweight NEMA-14 type stepper motor is fixed with two ties at the grip end of the pipe. The stepper motor actuates an internal belt system and as an inherent by-product produces slight audible and haptic noise when active. Inside the pipe, an aluminum pulley is fixed on the motor's axis. At the top end, two slots of 55 *mm* length and 5 *mm* width are cut into the pipe. Passing through these two slots, 450 *mm* away from the motor axis, a bolt with a diameter of 5 *mm* is fixed with a wing nut. Inside the pipe, this top bolt carries an aluminum pulley on small bearings. This allows the top pulley to spin without too much friction. Both pulleys and the toothed belt are widely available parts typically used in 3D printers. The internal weight is a custom designed 3D printed object of 60 *mm* length and 33 *mm* width. It contains four chambers filled with lead and has recesses for the belt. It is fixed on the belt and to minimize friction at the pipe's walls, the weight is designed to carry four bearings as wheels. Fig. 3 shows pictures of the assembled prototype. In total, the proxy weighs 440 *g* including a moving weight of 127 *g*, which gives a *moving weight : total weight* ratio of $\frac{127\,g}{440\,g} \approx 0.29 = 29\%$.

When the internal weight is shifted completely towards the grip end (for $p = 0$), the proxy's center of mass is located 13.6 *cm* from the pipe's bottom end. Shifting the weight with a step-resolution of $0.39\ \frac{mm}{step}$ over the complete range of 36.5 *cm* takes around 2.8 *s* with a speed of $\approx 0.13\ \frac{m}{s}$. If shifted maximally towards the top (for $p = 1$), the center of mass is at a distance of 24.5 *cm* from the pipe's bottom end. For each $p \in [0,1]$, the center of mass is thus interpolated between these two locations, covering a range of approximately 11 *cm*.

For the user input, we fixed a small pushbutton such as used in car keys on the outside of the proxy with a stretchable band and velcro fastener. This way, we could adjust the location of the button on the proxy to the user's hand size.

The proxy controller software runs on an *Arduino* microcontroller placed in a small backpack with a motor shield stacked on it. A 12 *V* rechargeable battery in the backpack serves as the power supply.

Integrating the physical proxy into a VE requires spatial registration of the real and the virtual object. To track the prototype, we use an *OptiTrack* system. A custom-designed rigid-body target made out of a 3D printed plug is attached to the top end of the pipe. It holds five wooden sticks with fixed reflective markers.

For recreating *Shifty*, we plan to publish a construction how-to online together with the 3D model data of the 3D printed parts.

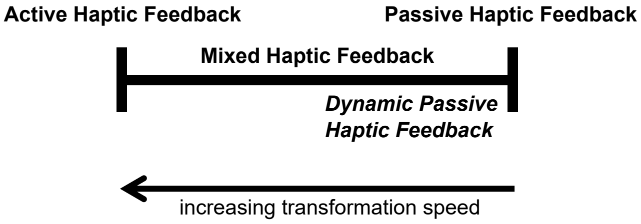

Fig. 4. The Active-Passive Haptics continuum.

4.2.2 Software

The C++ software controls the stepper and handles communication with the VR system. For this, the Arduino either connects to an existing WiFi network or opens a dedicated WiFi hotspot. Commands are sent by client applications using a custom C# API via network to the Arduino. Conversely, button events are communicated via TCP back to connected clients. The API offers a set of functions to move the weight in the proxy and to retrieve predictions of the transformation time.

4.3 The Active-Passive Haptics Continuum

When holding the internal weight at some position $p \in [0,1]$, *Shifty* is a classical passive haptic proxy object. It then provides the user with passive kinesthetic feedback and the actuator does not exert noticeable forces. However, when using an actuator to change a proxy's physical property, a continuous transition between active and passive haptic feedback becomes apparent. Imagine the virtual object in the user's hand changes its length over an interval of $t \approx 3\ s$. The proxy's weight would then be translated to the corresponding target position $p' \in [0,1], p \neq p'$ in this interval t to change the passive haptic properties of the proxy. The average corresponding shift speed would then be $v = \frac{|p'-p|}{t}$. For slow speeds v, the user perceives the desired change in the object's haptic feedback but no noticeable forces are exerted on him actively. However, for more instantaneous or even discrete tasks like picking up a virtual object, the theoretical change interval $t \rightarrow 0\ s$ and thus $v \rightarrow \infty$. Besides obvious mechanical problems that would arise, high translation speeds would transform the passive haptic proxy into an active haptic feedback device due to the arising repulsion forces. To avoid such undesired active forces, changes of the passive properties, even if theoretically instantaneous, have to be realized in an appropriate amount of time $t > 0\ s$. This prevents noticeable active forces as a side effect of the passive feedback transformation.

Consequently, the question arises how an instantaneous action, like picking up an object, implemented as an action that takes non-negligible time $t > 0\ s$, can be bridged with minimal impact on the user's immersion and perceived realism, despite existing visual-haptic mismatch during the transformation. To answer this question, we investigate six different strategies in the second experimental user study.

The transition between active and passive haptic feedback is flowing. Similar to the original Reality-Virtuality continuum [21], we classify haptic feedback in an *Active-Passive Haptics continuum* as sketched in Fig. 4. This continuum spans a space of *Mixed Haptic Feedback* in between the two opposite poles of AHF and PHF. Here the introduced concept of DPHF can be classified as a form of mixed haptic feedback close to the PHF pole. For DPHF proxy objects, an increasing transformation speed shifts the feedback closer towards the AHF end of the continuum. In Jeon and Choi's extended continuum [15], DPHF is a subclass of *haptic mixed reality* close to the *haptic reality* end, and spans across all degrees of virtuality in vision.

5 EXPERIMENT 1: CONTINUOUS CHANGE IN OBJECT LENGTH AND THICKNESS

In a first experimental evaluation, we investigate how a DPHF proxy like *Shifty* can enhance the perception of virtual objects that continuously change in form. For this, we put users in a VE and let them interact with two objects changing their length and thickness, respectively. In the physical environment, participants interact alternately with our weight-shifting proxy and with our proxy holding the internal weight stationary at the grip end, mimicking a conventional passive haptic proxy. This allows us to compare the perception of the virtual objects when using *Shifty* with the perception using an identical passive haptic proxy.

We expect *Shifty* to outperform the equivalent passive haptic proxy that does not change its kinesthetic feedback in the subjective measures realism and fun, but not in exertion.

5.1 Participants

12 volunteer participants took part in the first experiment (5 female, 7 male, avg. 28 years, between 21 years and 37 years old). 5 of them wore glasses or contact lenses during the experiment and 9 of them were right-handed, while 3 were left-handed. We also asked participants how regularly they play 3D video games on a scale from 1 (= never) to 7 (= regularly). The results showed that all types of gaming behavior were represented and the average score was 3.5. Moreover participants were asked to rate their previous experience with VR technology on a scale from 1 (= never used) to 7 (= regular use), and the average score of all participants was 1.6 with answers between 1 and 3.

5.2 Apparatus

The experiment was carried out in our lab using the *Shifty* prototype and a laptop to record the participants' answers and to run the *OptiTrack Motive* tracking software to track *Shifty*'s rigid-body target. Moreover, a *HTC Vive* head-mounted display (HMD) was used to track the participant. The HMD was additionally equipped with three infrared reflecting markers used to translate between the *Vive*'s and *OptiTrack*'s coordinate systems. To provide auditory feedback and to minimize the perceived noise of *Shifty*'s motor, all participants wore over-ear headphones.

The VE and the experiment itself were implemented using *Unity 5.3* which was executed on a powerful desktop PC. The data of the tracked rigid bodies were streamed with low latency via custom middleware and a local network from the laptop to the rendering PC. *Shifty* connected via WiFi to this local network and communicated with the Unity engine via the proxy's API.

During the experiment, participants stood in the center of the tracked space. While they could move freely, they did not need to walk around in the VE.

Fig. 1 shows a user interacting with *Shifty* and Fig. 5 depicts the setup with the exception that for the study, instead of a 3-camera *OptiTrack V120:Trio*, a 6-camera *OptiTrack* rig was used to ensure robust tracking and a large capture volume.

5.3 Procedure

Initially, each participant was informed about the course of the experiment and his tasks in the VE. *Shifty* was not shown to the participants before the experiment.

The experiment itself consisted of two phases. In each phase, *Shifty* was used once changing its weight distribution as introduced, and once always holding its internal weight at the grip end. By holding the weight stationary, it served as a classical PHF proxy.

The first phase was concerned with the user's perception of a virtual object continuously changing in length. Here, participants interacted with a virtual telescope that could smoothly extend and retract. The virtual telescope changed its length in four steps. Participants saw a floating virtual cube marked with a "+" as well as a cube marked with a "-" symbol. By intersecting one of the two cubes, the virtual telescope extended or retracted one step, respectively. In total, the virtual length changed from 50 cm to 200 cm in four equidistant steps. Fig. 6 depicts the completely extended and retracted telescope. The actual task of the participants was to stepwise extend the telescope from 50 cm to 200 cm and to freely swing and wield the telescope at each step. After that, participants had to stepwise retract it again. Finally they were asked questions about the perceived realism, exertion, the fun they had and their personal preference. As this procedure was performed once with DPHF and once with PHF, the only difference between both runs was whether the passive haptic feedback changed or whether it stayed unchanged. To exclude ordering effects, the order of DPHF and PHF runs alternated between participants.

Fig. 5. A user interacting with *Shifty* in our experimental setup. The user wears the *HTC Vive* and headphones. The rigid-body target on the proxy is tracked by an *OptiTrack* system.

The second phase was designed equivalently. Here, however, the virtual object did not change its length, but its thickness above the grip. It sized up in four steps from 200 cm^3 to 3000 cm^3. Fig. 6 shows the thinnest and thickest state of the object. The second phase was also conducted once with changing haptic feedback and once with constant passive feedback. At the end, the same set of questions was asked here again.

5.4 Design

The first experiment was designed as a within-subjects experiment. For each of the two independent phases, a Latin square for $n = 2$ was used 6 times to counterbalance the order of the haptic feedback modes.

The independent variable was the type of haptic feedback used. We tested two conditions: *DPHF* against *PHF*, or in other words we tested *using a proxy with changing weight distribution* against *using a proxy with constant weight distribution* as a baseline condition.

The dependent variables were the perceived realism, combined mental and physical exertion and enjoyment as a self-reported absolute value on a 7-point Likert scale and as a direct comparison between both types of feedback. Additionally, we also asked for the participants' personal preference in the form of a direct comparison. A final question asked the participant to rate on a 7-point Likert scale how much he perceived the physical proxy to really change its length or thickness with the virtual object after experiencing the DPHF feedback.

5.5 Results

The results of the first experiment are presented in the following. We start with the results of the first phase concerning changes in the length of the virtual object. After this, we present the results for the changing thickness.

5.5.1 Changing Length

The results of the absolute ratings for the perceived realism, the exertion (mental and physical demand combined) and the fun ratings are summarized in Fig. 7. Using Wilcoxon signed-rank tests, we compare the average ratings of each dependent variable for DPHF, i.e. using weight shift, against PHF, i.e. using a proxy with fixed weight distribution.

Regarding realism, participants were asked to rate how realistic they perceived the interaction with the object to be on a 7-point Likert scale from 1 (= very unrealistic) to 7 (= very realistic). According to a Wilcoxon signed-rank test ($Z = -2.814$, $p = .002$, $r = .81$), the difference in the perceived realism between the two conditions DPHF ($Mdn = 6.50$, $M = 6.25$, $SD = 0.87$) and PHF ($Mdn = 3.50$, $M = 3.58$, $SD = 1.93$) is significant on a significance level of $\alpha = 0.05$.

The results for the fun rating on a scale from 1 (= none) to 7 (= very much) were very similar. On the same significance level, a Wilcoxon signed-rank test ($Z = -2.781$, $p = .004$, $r = .80$) found the fun ratings to differ significantly between the DPHF condition ($Mdn = 6.00$,

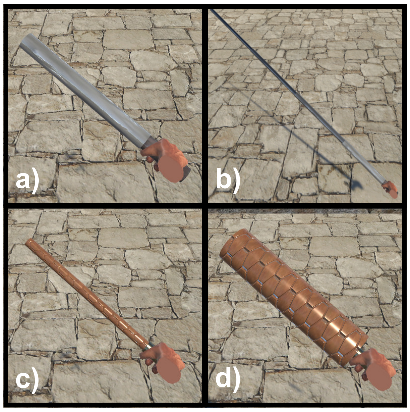

Fig. 6. The objects of the first experiment changing in length and thickness: a) the telescope object at $50\ cm$ length and b) at $200\ cm$ length, c) the rod-shaped object in the thinnest configuration and d) in the thickest configuration.

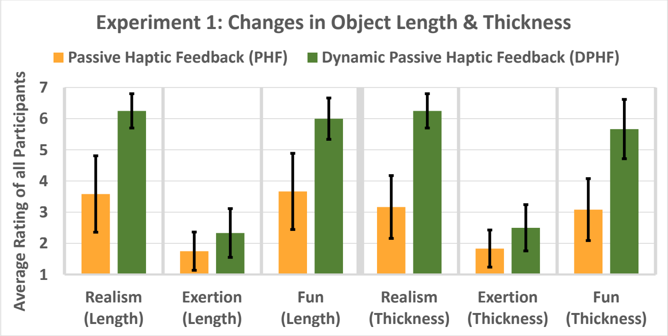

Fig. 7. The average ratings of all participants for perceived realism, exertion and fun of PHF (orange) and our DPHF approach with *Shifty* (green). The first three comparisons on the left relate to the virtual object changing in length, while the three comparisons on the right relate to changes in the virtual object's thickness. The error intervals depict the 95% confidence intervals.

$M = 6.00$, $SD = 1.04$) using weight-shifts and the PHF condition with a fixed weight distribution ($Mdn = 4.00$, $M = 3.67$, $SD = 1.92$).

With the increasing realism, the DPHF results for the mental and physical exertion on a scale from 1 (= not at all) to 7 (= very exertive) ($Mdn = 2.00$, $M = 2.33$, $SD = 1.23$) also increased compared to the PHF exertion ratings ($Mdn = 1.50$, $M = 1.75$, $SD = 0.96$). However, a Wilcoxon signed-rank test ($Z = -1.511$, $p = .250$, $r = .44$) did not find a significant difference.

Besides the reports of absolute ratings for the dependent measures, each of the 12 participants was asked to directly compare the conditions DPHF and PHF with respect to the factors realism, exertion, fun and personal preference. Here, participants consistently favored DPHF over PHF with regard to the realism of the haptic feedback (DPHF = 11, both equal = 0, PHF = 1), fun (DPHF = 11, both equal = 1, PHF = 0) and personal preference (DPHF = 11, both equal = 0, PHF = 1). Consistent with the absolute ratings, 7 out of 12 participants perceived DPHF as more physically and mentally demanding while no one perceived PHF as requiring more exertion. 5 perceived PHF and DPHF as requiring equal exertion.

When the participants were asked how strongly they felt that the object in their hand really changed its length, when in fact the proxy shifted its internal weight, a strong feeling was recorded. Participants could rate on a scale from 1 (= not at all) to 7 (= very strong feeling). The obtained average score ($Mdn = 6.50$, $M = 6.08$, $SD = 1.08$) was very high.

5.5.2 Changing Thickness

The results for the perception of the virtual object changing in thickness are very similar to the results gained for changing length. A summary of the absolute ratings can be seen in Fig. 7 as well.

As for changing length, the difference between the perceived realism of the DPHF condition ($Mdn = 6.00$, $M = 6.25$, $SD = 0.87$) and the PHF condition ($Mdn = 4.00$, $M = 3.17$, $SD = 1.59$) was statistically significant according to a Wilcoxon signed-rank test ($Z = -2.952$, $p = .001$, $r = .85$) for $\alpha = 0.05$.

The fun rating results also matched the results of the first phase. DPHF was rated to be significantly more fun ($Mdn = 6.00$, $M = 5.67$, $SD = 1.50$) than PHF ($Mdn = 3.50$, $M = 3.08$, $SD = 1.56$), as the results of a Wilcoxon signed-rank test show ($Z = -2.915$, $p = .002$, $r = .84$).

Although again slightly lower, the results for PHF ($Mdn = 2.00$, $M = 1.83$, $SD = 0.94$) did not differ significantly from the exertion ratings of DPHF ($Mdn = 2.00$, $M = 2.50$, $SD = 1.17$) according to a Wilcoxon signed-rank test ($Z = -1.725$, $p = .156$, $r = .50$).

The similarity to the results concerning length-changing objects continues when it comes to the direct comparison of DPHF and PHF. Participants again consistently favored DPHF over PHF regarding the realism of the haptic feedback (DPHF = 11, both equal = 0, PHF = 1), fun (DPHF = 10, both equal = 0, PHF = 2) and personal preference (DPHF = 10, both equal = 0, PHF = 2). 8 participants perceived DPHF as more physically and mentally demanding while 2 stated PHF required more exertion and 2 others said PHF and DPHF required equal exertion.

When the participants rated how strongly they felt the object in their hand changing its thickness, when in fact the proxy shifted its internal weight, a slightly lower average value ($Mdn = 6.00$, $M = 5.58$, $SD = 1.62$) was obtained. The difference from the rating in the first phase was not significant however, as the Wilcoxon signed-rank test results show ($Z = -0.641$, $p = .586$, $r = .18$).

5.6 Discussion

The first experiment was designed to show an example of how the DPHF proxy *Shifty* can be used to enhance object perception in VR. At the same time, the experiment should evaluate *Shifty*'s performance compared to an equivalent passive haptic proxy that does not change its passive kinesthetic feedback during runtime. The focus of this experiment lay on the user's qualitative perception of the virtual object. By taking the results about discrete weight distributions and their influence on VR proxy interaction [32] to the continuous level, we wanted to assess how well *Shifty* is suited to provide haptic feedback for virtual objects changing in form.

The results show that for virtual objects changing in length and thickness, the haptic feedback provided by *Shifty* is significantly more realistic and is enjoyed more by VR users, compared to an equivalent proxy with fixed weight distribution. Participants liked that the kinesthetic feedback adapts to changes in the virtual world. Very positive comments by the participants support these results. In a direct comparison of dynamic and fixed kinesthetic feedback, *Shifty*'s dynamic feedback was generally favored by participants. One even commented that "*without the motor, it wasn't any fun, especially not if experienced after [the condition with] the motor*".

Of course, the increased realism of *Shifty* comes at some cost: the interaction with longer, thicker or heavier objects increases the physical demand and might lead to fatigue. Our results did not show a significant increase in the user's exertion ratings, but that is likely to change when users interact for a longer period of time. Additionally, we would like to note that as a slight amount of audible and haptic noise could not be completely prevented, it cannot be entirely ruled out that these side effects contributed to the participants' experience to a minor degree as well. However, based on our observations, the results of previous investigations [32], given the experienced shifts and the participants' comments, the changing kinesthetic feedback was the primary and most significant factor enhancing the experience.

In addition to objects changing in form, we think that *Shifty*'s haptic feedback is also suitable to enhance the perception of virtual objects

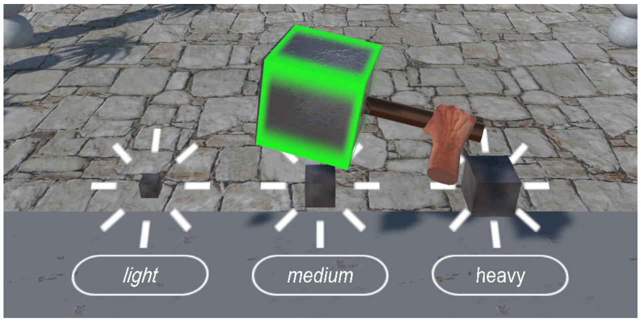

Fig. 8. Screen capture of the second experiment: The user picked up the heavy cube and is holding it in the target area.

that change their weight or their weight distribution, that are filled up or emptied, or that even change their material. We believe that by leveraging visual dominance, the perception of many types of object changes can, when visualized in synchronization with *Shifty*'s weight shift, be enhanced.

6 EXPERIMENT 2: PICKING UP VIRTUAL OBJECTS

While the first experiment investigated how *Shifty* can enhance the perception of objects changing over time, the second experiment is concerned with instantaneous events. In particular, we investigate how we can use *Shifty*'s dynamic feedback to enhance one of the most frequently used and crucial interactions in VR: picking up a virtual object. In most VR applications this requires the user to bring the physical VR controller close to the virtual object and to then press a button which snaps the object to the user's VR controller. By holding the button pressed, the virtual object stays attached, and releasing the button drops the object. In simulations or games, the VR controller is hereby typically visualized as a virtual hand or some interaction object similar to the actual controller.

Using *Shifty* as a VR controller, we leverage *Shifty*'s weight-shifting ability to enhance the feeling of weight. In our experiment, participants pick up a light-, a medium- and a heavy-looking object from a virtual inventory as depicted in Fig. 8. With the picked-up object they then solve a simple docking task by holding it in a target area. As we want to compare *Shifty*'s DPHF to the PHF provided by conventional VR controllers, we again mimic an equivalent PHF controller with *Shifty*. Similar to the first experiment, we compare a PHF baseline condition (*Shifty* holding the weight stationary at the grip) against five different DPHF conditions involving *Shifty*'s dynamic feedback. These five different conditions differ only in the visual and auditory feedback. By testing five different visualizations of the pick-up process, we try to find visual feedback that can compensate for the visual-haptic mismatch arising when *Shifty*'s weight is shifted for up to 2.8 s during pick-up. For this we again assess the participants' perceived realism, fun, personal preference and exertion. Additionally, we assess how disturbing the different conditions are with respect to immersion.

We expect the DPHF proxy *Shifty* to increase the realism and fun compared to an equivalent PHF proxy. Moreover, we expect the participants to favor *Shifty*'s feedback and that enhanced visualizations of the pick-up process even increase the perceived realism and fun for the user, while minimizing the disturbing impact of visual-haptic mismatch during the shifting process. Regarding exertion, we expect the PHF proxy to require the least, and *Shifty*'s dynamic feedback to be more physically demanding. However, we also expect appropriate visualizations to compensate for that to some degree, decreasing the perceived exertion compared to a standard visualization.

6.1 Participants

12 volunteer participants took part in the second experiment (3 female, 9 male, avg. 27 years, between 21 years and 37 years old). Half of the participants wore contact lenses or glasses and 10 were right-handed while 2 were left-handed. Compared to the first experiment, the average gaming experience was slightly lower, with a score of 2.9, and the VR experience was slightly higher with an average rating of 1.8. Here answers between 1 and 4 on the same 7-point Likert scale as in the first experiment were recorded.

Table 1. The Feedback Conditions of Experiment 2

Condition		Haptics	Sync. Visuals	Sync. Audio
Base	Baseline	PHF	None	None
Hapt	Haptic-Only	DPHF	None	None
Prog	Progress Bar	DPHF	Progress Bar	*Whoosh*
Scal	Scaling	DPHF	Scaling Up	*Whoosh*
Trans	Transparency	DPHF	Becoming Opaque	*Whoosh*
Mask	Masking	DPHF	Smoke Mask	*Whoosh*

6.2 Apparatus

As the setup for the first and second experiment is equivalent, please refer to Sect. 5.2: **Experiment 1: Apparatus**.

6.3 Procedure

As in the first experiment, *Shifty* was not shown to the participants before the experiment, and each participant was briefed about the course of the experiment and his tasks in the VE.

Each participant experienced six different conditions in succession. To account for ordering effects, the order of these conditions was counterbalanced using a Latin square among participants. For each condition, the participant's task was to pick up the light, the medium and the heavy virtual object and to hold it in a highlighted target area for 1 second. This ensured that the participants had comparative experiences for each condition. Starting with the completion of the second condition, questions were asked after the completion of all following conditions. In these questions, participants directly compared the last two experienced conditions. Here, we asked participants to state in which of the last two conditions the interaction with the objects after picking them up felt more realistic and in which the pick-up interaction was perceived as less disturbing regarding immersion. We further asked which condition took less exertion, which was more fun and finally, which one they would personally prefer. It was also valid to rate both as equal. After all conditions were experienced, participants were asked for their personal overall favorite condition.

All six conditions are summarized in Table 1. The PHF baseline condition (*Base*) represents the current state of VR controller interaction. It does not involve a change in the kinesthetic haptic feedback nor does it involve any special visual or auditory feedback. A second condition did not involve any special visual or auditory feedback either, but did use *Shifty*'s DPHF. This condition is called the haptic-only (*Hapt*) condition in the following. Besides *Base* and *Hapt*, four further conditions were tested. Like *Hapt*, they all used *Shifty*'s DPHF. In all DPHF conditions, *Shifty* adapted its inertia to the weight of the object picked up. *Shifty*'s internal weight moved to $p = 1$ when picking up the heavy object, to $p = 0.5$ when picking up the medium object and to $p = 0.1$ for the light object. Each of these four additional animation conditions involves the same auditory feedback combined with a different synchronized visual animation effect. The auditory feedback in all animation conditions is a *whoosh*-like sound that was played synchronously with the shifting weight. Visually, one condition displayed a progress bar showing the progress of *Shifty*'s weight shift when objects were picked up. We call this condition the progress condition (*Prog*). A second animation condition, the scaling condition (*Scal*), made objects scale up from the inventory-icon size to the object's actual size when picked up, synchronized with *Shifty*'s weight shift. A third condition, the transparency condition (*Trans*), transformed the object's transparency from transparent to opaque, and the masking condition (*Mask*) visually masked the picked-up object by displaying a thick smoke field around the object. The smoke only disappeared when *Shifty*'s weight shift was finished. Fig. 9 shows screenshots of these four visualizations.

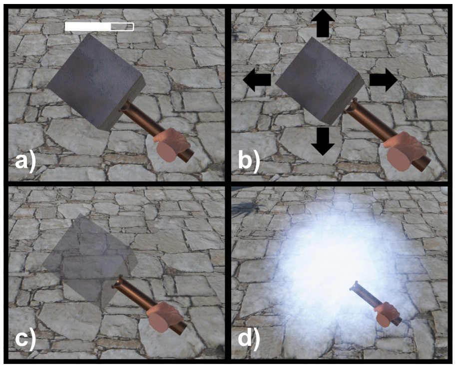

Fig. 9. The four different visualizations of the second experiment: a) the progress bar (*Prog*), b) the scaling animation (*Scal*), c) the transparency transformation (*Trans*) and d) the smoke mask (*Mask*).

6.4 Design

The second experiment is a within-subjects experiment. With six different feedback conditions, a Latin square for $n = 6$ was used twice to counterbalance the order of the different conditions.

The independent variable is the combination of haptic, visual and auditory feedback. Six different combinations were tested: the conditions *Base*, *Hapt*, *Prog*, *Scal*, *Trans* and *Mask* as introduced.

The dependent variables are the obtained measures regarding the perceived realism of the interaction with the objects after picking them up, the disturbing influence on the immersion during the pick-up interaction, the exertion, the enjoyment and users' personal preference. These measures are obtained as a set of direct comparisons.

As we always compared the last two experienced conditions, each participant was asked each of the five comparison questions five times. For the evaluation, we define a direct comparison of two conditions as a *match* played between these two conditions. Due to the Latin square design and the amount of participants, each condition played four times against each other condition, twice experienced before the compared condition and twice after. As a result a complete ranking table is computed for each dependent variable, i.e. each of the five questions. When a condition wins a direct comparison question, its score for the considered measure is increased by 2 points, while the losing condition's score stays the same. If two conditions are rated as equal, both score 1 point for the compared measure. After all 60 comparisons were recorded, all points scored by a condition were summed up and a final ranking table was computed for each measure. In this way, general tendencies towards a certain condition can be identified as favored conditions are more likely to win more comparisons than less-favored conditions. Since the second experiment focuses on the qualitative assessment of user preferences, we will discuss the resulting ranking, providing insights into which conditions are generally preferred or considered worse with respect to the five dependent measures. A more in-depth investigation and analysis is left to future work.

6.5 Results

The results of the second experiment are depicted in Table 2 summarizing the final ranking tables for all five dependent measures.

The scaling condition *Scal* scored best concerning the perceived realism of the interaction after picking up a virtual object. *Scal* was also classified as impairing the immersion least during the pick-up interaction and, together with the masking condition *Mask*, scored best concerning the participants' personal preference. Regarding the fun during the interaction, *Mask* scored highest. Concerning exertion, the baseline condition *Base* scored best, i.e. required the least exertion.

In the concluding question participants had to state their overall favorite condition. Here, 7 out of 12 participants chose the scaling condition *Scal* as their favorite, 2 chose the progress condition *Prog* and 2 others chose the haptic-only condition *Hapt*. 1 participant voted for the masking condition *Mask*.

6.6 Discussion

The second experiment shows how *Shifty* can be used to enhance the haptic perception of arbitrarily formed virtual objects with different weights. The drawback of current VR controllers is the fact that all virtual objects interacted with always feel the same regarding kinesthetic haptic feedback. This makes users perceive large and heavy virtual objects as unrealistically lightweight. The results of the second experiment show that a DPHF proxy designed like *Shifty* increases the perceived realism while interacting with virtual objects of different size and weight. By changing its weight distribution, *Shifty* provides compelling passive haptic feedback that enhances the perception of weight. In total, participants clearly favored the changing passive haptic feedback of *Shifty* over a simple PHF proxy object with fixed weight distribution.

6.6.1 DPHF vs. PHF

To evaluate the effect of DPHF, i.e. changing passive haptic feedback, we compare the results of our PHF baseline condition *Base* and our DPHF condition *Hapt*. Differences in the results of *Base* and *Hapt* can be attributed to the differences in the haptic feedback, as this is the only way *Base* and *Hapt* differ. Table 2 shows that considering the perceived realism during the interaction after picking up, the rated fun and the participants' personal preference, the DPHF condition *Hapt* clearly outperforms the PHF condition *Base*. This means that users have more fun and prefer interacting with objects that change their kinesthetic feedback. Moreover, they perceive the interaction with virtual objects as more realistic when using *Shifty*. In conformance with our expectations, *Base* was rated as requiring the least exertion and it had less negative influence on the immersion than *Hapt*. This is plausible, as in *Base*, the process of picking up is a very instantaneous action without enduring haptic change. This, in general, is not disturbing to the VR user, as no noticeable mismatch is involved, despite the general lack of haptic adjustment to the virtual object's weight. In *Hapt*, the user sees the same quick pick-up as in *Base*. Thus the user expects the process to be over as soon as the visual feedback suggests so. But as the weight still moves to its target position for up to 2.8 *s*, users can be irritated by the visual-haptic mismatch during this time. The lack of visual cues that help the user to understand the change in haptic feedback or its progress brings a risk of breaking the user's immersion. *Hapt* is thus ranked worst for this measure.

6.6.2 The Effect of Visual Animations

As the previous section summarized the effect of adding changing passive haptic feedback to a PHF proxy, we describe in the following how the perception of the user changes when the pick-up process is additionally animated visually and auditorily. For this, we compare the DPHF conditions *Hapt*, *Prog*, *Scal*, *Trans* and *Mask*.

Regarding the perceived realism, *Hapt* is outperformed by all conditions involving auditory and visual animations. This shows that the perceived realism can further be increased by animating the object during the pick-up process. This animation should be synchronized with the physical adjustment of the feedback. Furthermore, the results show that animations physically describing the haptic change, like *Scal* and *Trans*, yield the highest perceived realism. This is because they minimize the perceived visual-haptic mismatch during the shift. Scaling an object or making an object become more dense provides a plausible explanation for the changes in *Shifty*'s haptic feedback. Nonetheless, animations that are less related to the haptic change like *Prog* and *Mask* still improve the realism compared to *Hapt*. They still make the user aware of an ongoing change in the haptic feedback and allow him to estimate its duration.

Investigating the negative influence on the immersion during the shift, we see that all animations score at least as good as *Hapt*. Most score better than *Hapt* and some even better than *Base*. *Trans* and *Prog* fall behind *Base* in the ranking, as some participants perceived progress bars in general as disturbing and stressful and some were slightly distracted by the transparent objects. *Mask* and *Scal* scored better than *Base*. In general, *Scal* was noted to be the most natural and suitable animation by some participants as the haptic feedback

Table 2. Final Ranking Tables for all Measures in Experiment 2

Realism			**Least Disturbing**			**Exertion**			**Fun**			**Preference**		
#	Condition	Score	#	Condition	Score	#	Condition	Score	#	Condition	Score	#	Condition	Score
1	*Scal*	29	1	*Scal*	25	1	*Base*	11	1	*Mask*	30	1	*Mask*	30
2	*Trans*	27	2	*Mask*	22	2	*Trans*	17	2	*Scal*	26	1	*Scal*	30
3	*Prog*	23	3	*Base*	21	3	*Scal*	21	3	*Prog*	22	2	*Prog*	18
4	*Mask*	20	4	*Trans*	18	4	*Hapt*	23	4	*Trans*	17	3	*Trans*	17
5	*Hapt*	18	5	*Prog*	17	4	*Mask*	23	5	*Hapt*	16	3	*Hapt*	17
6	*Base*	3	5	*Hapt*	17	5	*Prog*	25	6	*Base*	9	4	*Base*	8

matched the visual effect of growing objects. The smoke masking effect in *Mask* was perceived differently. While some could explain the effect as the output of the virtual rod in the hand, others could not relate the effect to the object or interaction at all. Thus for some users, the immersion was very well sustained as the effect did fit into the virtual world. Others, however, were rather distracted by it. In the general case, it certainly depends on the application and scenario. The masking effect should match the context and should be explainable. In games, for example, one can think of effects that match the setting of the game. In summary, DPHF comes with the risk of breaking the immersion when the haptic change is not synchronized with the visual or auditory channel. However, the results show that a good and plausible visual and auditory animation matching the change in haptic feedback can lower this risk or even improve the immersion.

Adding more realistic inertial feedback means more physical demand. Here, not simulating an object's weight, as in *Base*, is certainly the least demanding way. The physical demand of DPHF was slightly higher but equivalent for all DPHF conditions. Thus regarding the exertion measure, the mental demand makes the difference. As *Mask* and especially *Prog* were perceived by some as rather stressful or distracting, they are ranked no better than *Hapt*. *Trans* and *Scal* were considered more suitable and scored better than *Hapt*. This shows that explainable and suitable animations can ease the interaction by decreasing mental demand.

Considering fun, the most spectacular animation, the smoke masking *Mask*, clearly leads the score, followed by the most realistic condition *Scal*. Both were generally considered very interesting and fun, even by those participants who could not really relate the masking effect to the interaction or the virtual object. Conditions *Prog* and *Trans* scored slightly less, but higher than *Hapt*. This ranking emphasizes that more noticeable and less subtle effects in combination with DPHF can increase the entertainment factor.

Finally, considering personal preferences, 2 groups among the DPHF conditions can be identified: the generally preferred conditions *Mask* and *Scal* both scoring highest and the remaining conditions *Prog*, *Trans* and *Hapt*. The condition rated most realistic, *Scal*, thus seems to be as popular as *Mask*, the masking animation rated most entertaining. Less popular is the progress bar in *Prog*, which was described as rather annoying, and the subtle transparency animation *Trans*.

When asked for their overall favorite condition, participants clearly preferred realism over the entertaining factor with more than half of the participants choosing *Scal*.

In summary, participants clearly favored DPHF over PHF. The favorite animations were the entertaining masking animation *Mask* and the realistic scaling animation *Scal*, with *Scal* being the overall favorite.

7 CONCLUSION

In this paper, we introduced a class of passive haptic proxy objects for VR that use actuators to modify their passive haptic feedback. We call this class *Dynamic Passive Haptic Feedback* (DPHF) and we introduced *Shifty*, a DPHF proxy that automatically changes its internal weight distribution to change its inertial feedback.

In two experiments, we showed that *Shifty* can haptically represent a large set of virtual objects more realistically than an equivalent PHF proxy. We showed that *Shifty* can enhance the perception of virtual objects that continuously change in length or thickness. We could show that the perceived realism when interacting with *Shifty* is significantly higher, that users have significantly more fun and that users generally prefer interacting with our DPHF proxy compared to an equivalent PHF proxy. Based on our results, we believe that with weight-shifting proxy objects like *Shifty*, we can enhance the perception of changes in an object's shape, material, weight, weight distribution or content as well. Interactions like filling or emptying virtual objects could likewise be enhanced. Besides continuous changes of the haptic feedback, we also considered instantaneous events that imply changes in the kinesthetic haptic feedback. For this, we used *Shifty* as a VR controller and experimentally investigated how arbitrary virtual objects of different virtual weight could be picked up with *Shifty*. We found that theoretically instantaneous haptic changes cannot unrestrictedly be simulated by fast transformations of the proxy's properties due to the arising repulsion forces. This led to our definition of the Active-Passive Haptics continuum displayed in Fig. 4. Thus *Shifty* moves its internal weight with a speed that does not exert noticeable active forces on the user. To compensate for the arising dynamic visual-haptic mismatch, we further investigated visual and auditory animations. We found that appropriate visualizations matching the perceived haptic change, even if abstract, can decrease the negative impact on immersion and increase the perceived realism and fun. In our experiment, scaling a picked-up virtual object while *Shifty*'s internal weight moves was perceived as most realistic and was generally favored by participants.

DPHF proxy objects such as *Shifty* mix elements from active and passive haptics. With *Shifty*, we managed to combine the advantages of both worlds: *Shifty*, while primarily a passive haptic proxy, made out of cheap and widely available materials, offers a greater generality than conventional passive haptic proxies due to its actuating motor that changes its weight distribution. At the same time it still is ungrounded and mobile. The underlying concept of a VR controller that shifts weight has a great potential to complement today's VR controllers. These VR controllers offer sophisticated vibrotactile feedback and by this already enhance a large set of interactions in the VE. However, they still lack the feature of changing kinesthetic feedback. By combining the vibrotactile feedback of current VR controllers and *Shifty*'s DPHF, novel controllers that provide convincing haptic feedback for VR could be designed.

While *Shifty* can enhance the perception of mass and inertia very well, it still has some limitations. Currently, *Shifty* produces slight vibration and noise as a by-product of the weight shift and when heavily shaken. In future iterations, this could be further reduced by damping the motor and the internal weight. However, most of the participants perceived this effect as complementary feedback similar to the vibration feedback used by current VR controllers and only some found it slightly disturbing. Despite that, *Shifty* does not change its actual size and the grip grasped by the user always feels the same in terms of texture and shape. Moreover, *Shifty* cannot simulate arbitrary forces or weights. Our experiments showed, though, that the range of inertia that *Shifty* is capable to produce suffices to enhance the interaction with typical everyday objects in the VE. Finally, when considering its physics, a special case exists. By holding the proxy in an upright position, the effective lever arm vanishes and the user only perceives inertia when trying to move the proxy. However, as this special case could be prevented using redirection techniques, it does not restrict *Shifty*'s area of application.

8 FUTURE WORK

Future work could integrate weight-shifting feedback into vibrotactile VR controllers. Apart from changes in the virtual object's length and thickness, it would be interesting to investigate further types of object changes that can be enhanced by weight shifts. Moreover, future studies could explore the potential of holding *Shifty* horizontally, grasping it near the center. This way, shifts to the right and left could be implemented, which could enhance interactions that involve balancing a virtual object. Considering our second experiment, future investigations could compare the animations in an in-depth analysis and look at other combinations of haptic, visual and auditory feedback. As all introduced animations can be considered orthogonal to each other, it would be interesting to see if combining them yields further improvements regarding the compensation for the transformation mismatch. Additionally, as the cubes used in the second experiment were basic primitives, investigations with objects of different shape are interesting as well and a direct comparison of *Shifty*'s feedback with the feedback of real objects of different weight would certainly be great to study the stimulation realism. Considering *Shifty* as an input device for user interfaces in VR, we plan to investigate how *Shifty*'s changing inertia affects user interface interactions.

Aside from *Shifty*, future research should investigate other types of DPHF proxy objects that use actuators to change the passive haptic feedback. Adaptations in all dimensions of proxy properties like for example shape, size, temperature, texture, absolute weight, and combinations thereof, can be imagined.

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