Beyond Hardware: Enhancing Haptic Design for Virtual Reality Through Perceptual Illusion Techniques

Carolin Stellmacher*
cstellma@uni-bremen.de
University of Bremen
Bremen, Germany

André Zenner*
andre.zenner@uni-saarland.de
Saarland University & DFKI
Saarbrücken, Germany

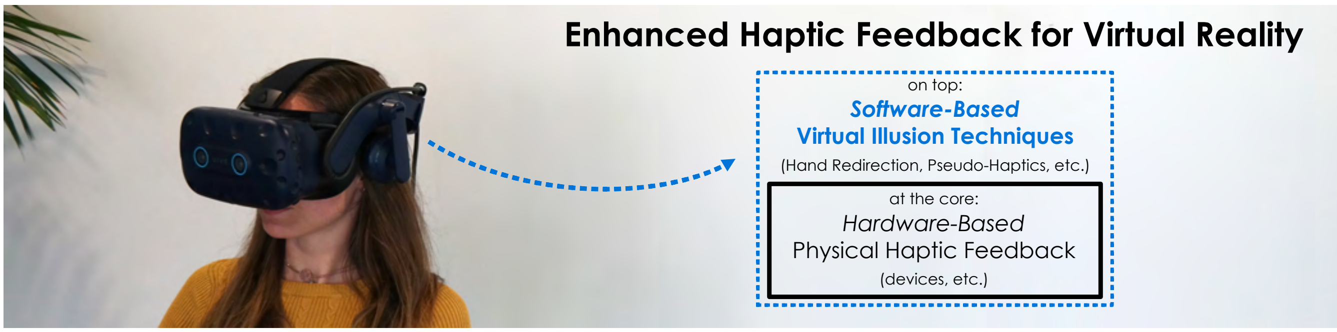

Figure 1: We propose to investigate the potential of software-based techniques that leverage perceptual illusions for enhancing the feedback provided by haptic devices for VR.

ABSTRACT

In many application domains, haptic feedback can only be conveyed through physical actuation of the user's body. The domain of virtual reality (VR), however, is different in this regard and offers exciting new possibilities when it comes to conveying the haptics of virtual worlds to users. Since VR systems have full control over the visual input of users, software-based techniques have been proposed that can enhance the perceived quality and flexibility of traditional haptic feedback solutions. By taking advantage of perceptual phenomena like multisensory integration, visual dominance, or change blindness, these so called *perceptual illusion techniques* for VR cleverly exploit the particularities of human perception. In this paper, we present examples of our previous work on enhancing the haptic design freedom for VR through techniques like hand redirection and pseudo-haptics, and outline directions for future research in this emerging domain.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Haptic devices**.

KEYWORDS

virtual reality, haptic feedback, hand redirection, pseudo-haptic feedback, haptic perception

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*Both authors contributed equally to this paper.

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1 INTRODUCTION

Traditional haptic feedback methods rely primarily on solutions that physically interact with the user's body. To convey tactile stimuli, for example, actuators are placed on the user's skin conveying vibration or electrical stimuli. Complementarily, to convey kinesthetic perceptions, robotic actuators are usually pushing or pulling the user's body.

Considering our perception with all our senses as a whole, we can observe that humans are very visually-driven, with visual perception often dominating multisensory experiences – a phenomenon known as *visual dominance* [5]. Just like our perception, so is the application domain of virtual reality (VR) very visually-driven. Modern VR systems employ head-mounted displays to control what the user sees. This unique control over the user's strongest sensory channel thus comes with great opportunities.

As multisensory perception is an inherently complex process, perceptual sciences have observed several perceptual phenomena that can occur and affect how humans perceive the world and interactions within it. Examples for such phenomena are the laws of multisensory integration, visual dominance, or change blindness. In VR, these phenomena can be targeted by interaction techniques to affect how users perceive interactions within immersive virtual environments. Such *perceptual illusion techniques* are multifaceted and range, e.g. from redirected walking [8, 14], over hand redirection [6, 24], to pseudo-haptics [7, 13].

In this position paper, we put forward the idea of extending the design space for haptic experiences in VR through illusion techniques. As these techniques are primarily software-driven, we further argue that this extension happens inclusively, relaxing the need to work with complex and costly hardware. Instead, software-methods open novel possibilities for haptic design that can be used on top of classical hardware-based haptic systems as sketched in Figure 1. Yet, we also argue that it currently is still understudied how to best design such *combined haptic feedback techniques* and how tools should look like that would optimally support developers in authoring combined haptic feedback experiences in VR.

In the following, we will briefly introduce our research backgrounds and present examples of our work in this area. Our position paper is concluded with ideas for future research towards more inclusive haptic design leveraging illusion-based techniques in VR.

2 BIOGRAPHY & RESEARCH BACKGROUND

2.1 Carolin Stellmacher

Carolin Stellmacher has been working towards a PhD in the field of human-computer interaction and VR haptics since March 2020 at the University of Bremen, Germany, under the supervision of Prof. Dr. Johannes Schöning. In her research, she is dedicated to designing haptic interfaces for VR and mixed reality (MR) that incorporate and extend modern handheld hardware and incorporate haptic illusions to enable haptic experiences.

A particular focus in her haptic design considerations has been to provide users with a meaningful and appropriate haptic sensation tailored to the input and interaction technique used. For example, her custom-built haptic VR controller *Triggermuscle* (see Figure 3a) renders varying levels of resistance at the trigger button to convey a sense of object heaviness [9]. To strengthen the illusion of weight, the follow-up research combined Triggermuscle's hardware approach with the known software method of manipulating the control-display (C/D) ratio [13], drawing on the benefits of the perceptual illusion technique (see Figure 3b and section 3.1). Further, applying the C/D ratio manipulation towards the simulation of *dynamic* changes during the interaction VR was the focus of another work, which enabled users to perceive changes in object heaviness, e.g. when filling a cup of water, using only a consumer VR controller and its built-in vibrations [11].

In her most recent work, Carolin Stellmacher expands the design possibilities of using mobile devices as handheld haptic interfaces for haptic experiences in MR [12]. The explored design space offers a set of user-centred gestures for MR object exploration using a mobile phone and provides practical implications for the design of future mobile devices as haptic interfaces for MR experiences.

2.2 André Zenner

Dr. André Zenner is currently a postdoctoral researcher at Saarland University and at the German Research Center for Artificial Intelligence (DFKI) in Saarbrücken, Germany. He has studied computer science and obtained his PhD [15] from Saarland University in 2022 under the supervision of Prof. Dr. Antonio Krüger. His research focuses on human-computer interaction and VR, with a specific focus on haptics for VR and perceptual illusion techniques.

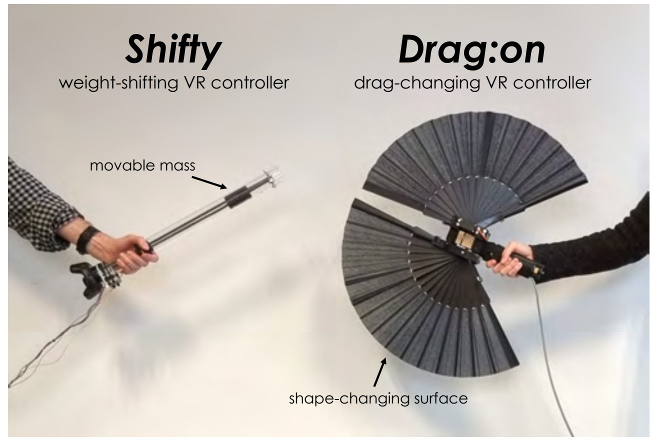


Figure 2: The weight-shifting VR controller *Shifty* [20] (on the left) and the shape-changing VR controller *Drag:on* [21] (on the right). *Shifty* conveys kinesthetic properties of virtual objects (e.g., their weight or length) by changing its moment of inertia. *Drag:on* additionally uses changes in the controller's air resistance felt by the user when moving the controller through the air during the interaction.

Examples of his research contributions include the two handheld haptic VR controllers *Shifty* [20] and *Drag:on* [16, 21] shown in Figure 2. Both controller designs stand out by being mechanically simple, low-cost, and still able to convey kinesthetic effects in VR without the need for strong and heavy actuators. André Zenner has also worked in the field of perceptual illusion techniques for VR and contributed several novel hand redirection algorithms [18, 24] and psychophysical investigations [17, 18, 22, 24] that inform about the detectability of such techniques. Furthermore, his research has covered the combination of hard- and software-based approaches to VR haptics [1, 3, 4, 13, 15, 23, 26].

Following an open-science approach, André Zenner has released several open-source repositories that allow others to build upon the software and physical prototypes developed in his research. These include, e.g. building instructions for *Shifty*[1] [20] and *Drag:on*[2] [21], the *Virtual Reality Hand Redirection Toolkit*[3] [19], and the *Unity Staircase Procedure Toolkit*[4] [25].

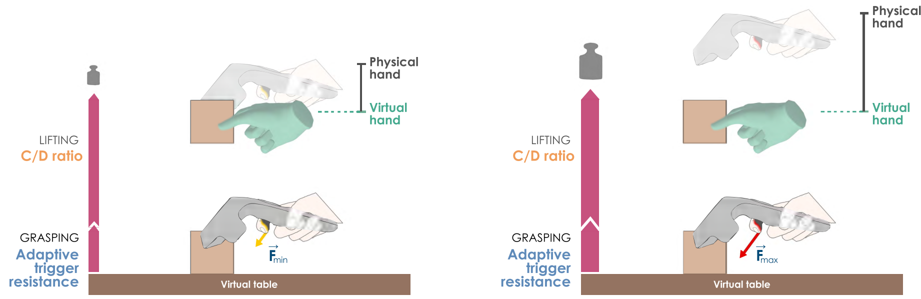
3 PERCEPTUAL ILLUSION TECHNIQUES FOR ENHANCED HAPTIC DESIGN FREEDOM

Perceptual illusion techniques for VR are software-driven and thus conceptually orthogonal to hardware-based haptic feedback solutions. For this reason, hardware-based feedback and software-based illusions can be combined.

In the following, we briefly review two previous research projects of ours in which we investigated such combinations. Our results

[1]https://github.com/AndreZenner/shifty
[2]https://github.com/AndreZenner/dragon
[3]https://github.com/AndreZenner/hand-redirection-toolkit
[4]https://github.com/AndreZenner/staircase-procedure

(a) The haptic VR controller *Triggermuscle* adapts the level of trigger resistance to simulate different virtual weights in VR [10].



(b) An example of combined haptic feedback to convey a sense of object weight in VR: Triggermuscle's adaptive trigger resistance (during grasping) and the pseudo-haptic technique of manipulating the control-display (C/D) ratio (during lifting) [13].

Figure 3: Haptic design utilising hardware- and software-based approaches for weight perception in VR.

indicate that combined feedback allows for more haptic design freedom as we found software-based illusions to enhance the haptic rendering capabilities of the investigated systems – without requiring modifications of the haptic hardware.

3.1 A Pseudo-Haptics Example

The first example combines the haptic VR controller Triggermuscle and its adaptive trigger resistance (see Figure 3a) [9] with the pseudo-haptic technique of manipulating the control-display (C/D) ratio to convey a sense of object weight. Here, the employment of two techniques allows the integration of two multisensory weight cues for the simulation of virtual weight in VR. The level of resistance provides cutaneous stimuli when pulling the trigger and conveys a sense of object heaviness during grasping. Upon lifting, the manipulated C/D ratio applies a movement gain to users' physical arm movements. The resulting displacement between the visually displayed hand in VR and users' tracked hands induces a proprioceptive sensation while an object is moved through space. The haptically augmented lifting interaction is depicted in Figure 3b.

We conducted an experiment in which we tested both individual techniques against the combined approach. Our findings show that users were able to differentiate smaller weight differences when they were exposed to both haptic stimuli during the interaction. The combined weight simulation also allowed users to determine weight differences faster. The study outcome indicates that by augmenting the VR controller with visual manipulation in VR, not only can more distinct weight differences be rendered, but also the range of virtual weights extended. By providing haptic stimuli at two different moments in time, the combined haptic feedback created a continuous VR weight illusion throughout the interaction. In future research, this concept could also be applied to new combinations of haptic technology and software techniques to explore the perceptual benefits for haptic experiences beyond virtual weight.

3.2 A Hand Redirection Example

A second example of how an illusion technique can enhance the haptic feedback in VR, and thus the design freedom of feedback developers, is the combination of the weight-shifting VR controller *Shifty* [20] with unnoticeable hand redirection [2, 22]. In a previous project [15, 23, 26], we considered the scenario of picking up a virtual stick and haptically rendering its weight distribution, i.e., its center of mass location. We used *Shifty* as a haptic proxy that represented the virtual object to be picked up, and leveraged its capability to shift its internal mass in order to convey different states of balance. The maximum weight shift that can be conveyed by this method, however, is constrained by the physical parameters of the proxy itself (e.g., max. shift range and built-in mass), and cannot be increased without physical modifications – or can it?

In two perception experiments, we found that by applying the perceptual illusion technique of hand redirection, we can significantly increase the conveyable shift magnitude. For this, the system redirected the user's physical grasp to a location farther away from the physical center of mass of the proxy to effectively increase the perceived lever when picking up the object – magnifying the perceived weight shift as illustrated in Figure 4. In addition, a combination of weight-shifting and hand redirection also allowed for greater dislocation between the virtual object and the physical proxy to go unnoticed by users. To achieve these results in our experiment, the illusion technique was applied to an amount that was below perceptual detection thresholds [22] (i.e., users did not notice that they were being redirected in most cases).

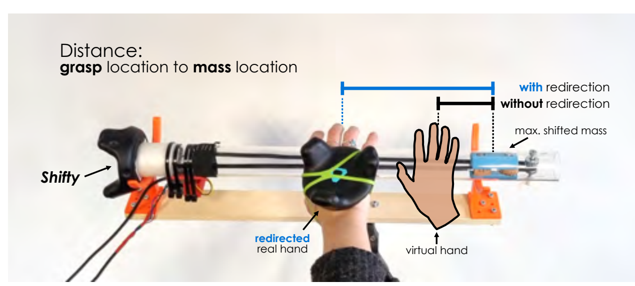


Figure 4: By combining a technique known as *hand redirection* with the haptic feedback provided by the weight-shifting VR controller *Shifty*, significantly greater virtual mass shifts can be conveyed than with the physical device alone [23, 26].

4 CONCLUSION & OUTLOOK

The results of our previous experiments showed that by applying software-based techniques on top of physical techniques, the haptic rendering capabilities of VR systems can be enhanced significantly. In the context of haptic design, this means that designers of haptic VR experiences are granted more design freedom. Using perceptual illusion techniques, haptic designers can adapt the feedback provided by a VR application without the need to change the feedback provided by the haptic hardware. Instead, adapting the visualization of interactions in VR can be enough to convey certain effects.

While some research in this field has already been conducted and important benefits of combined methods have been found, we argue that still more research is necessary to uncover further combinations of physical and virtual techniques that can empower haptic designers. In parallel, we see a need for novel tools and recommendations for best practices, which help reduce the complexity that is introduced by the combination of hard- and software-based techniques. Moreover, we propose that the results that have been published in this domain up to now be summarized and compiled into a set of guidelines. Such guidelines could help designers apply combined methods, and help researchers identify important aspects to be investigated in future research.

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