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The final version of record is available at http://dx.doi.org/10.1109/TVCG.2021.3067777

Combining Dynamic Passive Haptics and Haptic Retargeting for Enhanced Haptic Feedback in Virtual Reality

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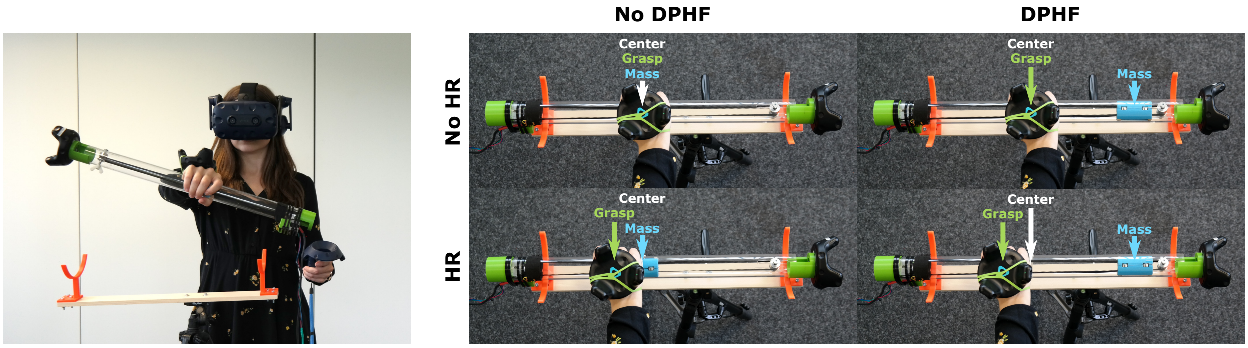

Fig. 1. We combine Dynamic Passive Haptic Feedback (DPHF) (here: a weight-shifting prop) and Haptic Retargeting (HR) (here: unnoticeable hand redirection) in a proof-of-concept scenario to simulate different weight distributions in a virtual stick. The left image illustrates how participants lift up a physical prop in our experiments to compare the haptic rendering capabilities of DPHF and HR against our proposed combined technique. The matrix on the right depicts the real-world view of our 4 tested haptic feedback conditions in the *Similarity* experiment. Each technique is in its state to render its respective maximum weight shift.

Abstract— To provide immersive haptic experiences, proxy-based haptic feedback systems for virtual reality (VR) face two central challenges: (1) similarity, and (2) colocation. While to solve challenge (1), physical proxy objects need to be sufficiently similar to their virtual counterparts in terms of haptic properties, for challenge (2), proxies and virtual counterparts need to be sufficiently colocated to allow for seamless interactions. To solve these challenges, past research introduced, among others, two successful techniques: (a) Dynamic Passive Haptic Feedback (DPHF), a hardware-based technique that leverages actuated props adapting their physical state during the VR experience, and (b) Haptic Retargeting, a software-based technique leveraging hand redirection to bridge spatial offsets between real and virtual objects. Both concepts have, up to now, not ever been studied in combination. This paper proposes to combine both techniques and reports on the results of a perceptual and a psychophysical experiment situated in a proof-of-concept scenario focused on the perception of virtual weight distribution. We show that users in VR overestimate weight shifts and that, when DPHF and HR are combined, significantly greater shifts can be rendered, compared to using only a weight-shifting prop or unnoticeable hand redirection. Moreover, we find the combination of DPHF and HR to let significantly larger spatial dislocations of proxy and virtual counterpart go unnoticed by users. Our investigation is the first to show the value of combining DPHF and HR in practice, validating that their combination can better solve the challenges of similarity and colocation than the individual techniques can do alone.

Index Terms—Virtual reality, dynamic passive haptic feedback, haptic retargeting, hand redirection, proxy-based haptic feedback.

1 Introduction

Immersive virtual reality (VR) systems aim to let users experience a feeling of presence [47] as they interactively explore virtual environments (VEs). To achieve this goal, VR systems provide the user with synthetic stimuli, of which visual, auditory and haptic cues are among the most important. While modern VR systems already achieve a high visual and auditory rendering quality, providing appropriate haptic feedback for interactive VEs in which users are able to freely interact with virtual objects and perceive their interactions through the sense of touch remains a great challenge. This challenge brought to light a diverse range of haptic rendering concepts (e.g. [8, 12, 23, 56, 63]) and devices (e.g. [4, 9, 44, 57, 63]). A technique that has proven very successful in a wide range of application areas is based on leveraging physical props. This technique of *passive haptic feedback* [21, 23] utilizes physical objects that serve as proxies for virtual objects the user touches and interacts with in the VE.

Proxy-based haptic feedback can provide a highly realistic haptic rendering quality as users perceive real objects in both a tactile and kinesthetic way. In contrast to active haptic techniques based on robotic actuation [36, 56] or wearable devices [5, 19], the technique often requires only low-fidelity props [23] made out of cheap and readily available materials instead of complex actuation, and does not constrain the interaction space, as props can be portable. Proxy objects can be tracked using commodity hardware and are thus relatively cheap to integrate into any VR experience. One main downside of this technique, however, becomes apparent as VEs increase in complexity and scale. As the number of interactable virtual objects in a VE increases, the number of required physical proxies increases too, and as virtual objects change any virtual properties, the corresponding props would need to be replaced – two factors limiting the scalability of proxy-based haptics.

To mitigate these issues, past research identified two central challenges to be solved for successful proxy-based haptics [35, 52, 61, 66]:

1. ***Similarity***: proxies and virtual objects must be sufficiently similar in terms of haptic properties to convey convincing perceptions.

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Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org. Digital Object Identifier: xx.xxxx/TVCG.201x.xxxxxxx

2. ***Colocation***: proxies and virtual objects must be spatially colocated to enable seamless interactions.

To tackle these challenges, researchers have proposed several approaches, among them the concepts of:

1. **Dynamic Passive Haptic Feedback (DPHF)** [63]: a hardware-based technique that extends props with actuation enabling a dynamic adaptation of their physical properties at runtime. The technique thus aligns the provided passive haptic feedback to different virtual objects – tackling the challenge of *Similarity*.
2. **Haptic Retargeting (HR)** [3, 29]: a software-based technique manipulating the virtual hand rendering to control the real hand movement. By leveraging hand redirection to bridge spatial offsets, users can seamlessly touch virtual objects that are dislocated from their proxies – tackling the challenge of *Colocation*.

Both of these techniques have received significant research attention lately, and showed promising results. Up to now, however, these concepts have only been considered individually, although they promise to complement each other when it comes to solving the challenges of *Similarity* and *Colocation*. Their combination has only recently been proposed in two thought experiments [66], but has never been validated in practice.

Motivated by this gap in research, we practically combine both concepts in a proof-of-concept scenario focusing on the haptic rendering of weight shift in proxy-based VR. Our investigation showcases and validates the benefits of combining DPHF and HR to tackle the challenges of *Similarity* and *Colocation* in a better way than is possible with the individual techniques. Our contribution is four-fold:

1. We propose and implement a technique combining DPHF and HR to haptically render weight shifts inside a virtual stick.
2. In a perceptual experiment, we validate that the combination of DPHF and HR outperforms the individual techniques regarding a *Similarity* metric by rendering significantly greater weight shifts.
3. Through the same perceptual experiment, we show that users overestimate weight shifts in VR.
4. In a psychophysical experiment, we validate that the technique combining DPHF and HR outperforms the individual techniques regarding a *Colocation* metric by making significantly larger dislocations of proxy and virtual objects go unnoticed by users.

In the following we present related research and our investigated proof-of-concept scenario. We provide detail on the metrics we use to assess the success of the investigated techniques in solving the challenges of *Similarity* and *Colocation*, and introduce our proposed combination of DPHF and HR to render weight shifts inside a virtual stick. Following a statement of our hypotheses, we present the conducted experiments along with the obtained results. The paper concludes with a discussion of the results and directions for future work.

2 Related Work

The following section reviews the central challenges of proxy-based haptic feedback in VR, as well as previous research on DPHF and HR. We further summarize how both techniques have been combined with other concepts to improve their haptic rendering capabilities.

2.1 Proxy-Based Haptic Feedback & Involved Challenges

Hinckley et al. [21] introduced the idea of leveraging physical props to provide haptic feedback for virtual objects in the early 90s. Today this approach is referred to as *passive haptic feedback* [23] and has since received significant research attention [8, 14, 22, 46, 52]. Passive haptic feedback represents an extreme end of the Active-Passive Haptics continuum [63] and in contrast to active haptics does not utilize any actuation to convey haptic sensations. Instead, users immersed in VR receive tactile and kinesthetic sensations just through interaction with real physical objects, which are referred to as props or proxies in this context. As a user touches a virtual object in the scene, the user's real hand touches the physical proxy and its inherent physical properties such as its shape, size, weight, material, temperature, etc. define the passive haptic feedback, i.e. the haptic cues, sensed by the user.

Passive haptics can convey highly realistic perceptions and previous research could show that it can increase presence and has a positive effect on training transfer [23]. Due to the utility of low-cost and low-fidelity props, passive haptics has been successfully employed in a wide range of VR applications including, for example, sports [15, 31], data visualization [21, 67], retail [62], gaming [14, 53], and training [23, 40]. One of the main advantages of props is that they are usually ungrounded, do not involve costly and complex mechanics to produce human-scale force feedback, and can be tracked with consumer hardware. The drawback of conventional proxy-based feedback, however, is that the technique suffers from scalability and generalizability issues [52, 61]. These issues become striking when users engage with complex VEs in which virtual objects might change their properties, or which are populated with many different virtual objects users can interact with. In such scenarios, the number of props in the real environment increases with the number of virtual objects and proxies would need to be modified when properties of their virtual counterparts change.

To this end, Simeone et al. [45, 46] introduced the concept of *Substitutional Reality*, proposing to flip the relationship between real and virtual world by substituting any physical object in the environment with an appropriate virtual counterpart in VR. As any mapping of proxy to virtual object encompasses a certain mismatch, past research studied how users perceive mismatched textures [11, 28], shapes [28, 33, 46], temperatures [69], weights [46], and weight distributions [60].

To achieve convincing perceptions with proxy-based haptics, recent research identified two central criteria that need to be met [35, 61]: *Similarity* and *Colocation*. Physical props need to be sufficiently *similar* to the virtual objects they represent in terms of haptic properties to ensure coherent perceptions of the virtual objects. Additionally, proxies need to be sufficiently *colocated* with their virtual counterparts to enable seamless and intuitive interactions. Strandholt et al. identified these two criteria to be orthogonal [52], meaning that one criterion can be perfectly fulfilled, while the other challenge is not solved adequately (e.g. if a virtual object is represented by a dislocated physical replica). Our investigation will use these two criteria as a starting point to formulate metrics that assess the performance of proxy-based techniques. As optimal feedback requires solving both challenges simultaneously and as optimally as possible, a range of such techniques have been introduced in the past that extend the concept of passive haptics. Two of them are introduced in the following sections.

2.2 Dynamic Passive Haptic Feedback (DPHF)

Dynamic Passive Haptic Feedback (DPHF), introduced by Zenner and Krüger [63], mixes active and passive haptics. It tackles the challenge of *Similarity* by enabling physical proxies to represent a greater variety of virtual objects convincingly than purely passive proxies. Conceptually DPHF is located between the two extreme ends of the Active-Passive Haptics continuum [63], but close to the passive end, as it still fully relies on passive haptic sensations. The technique leverages proxies equipped with basic actuation (e.g. motors). These actuators are not used to render active forces, but only to change the physical state of the proxy. In other words, DPHF changes the proxy's passive haptic properties to match them with those of different virtual objects.

As an original example, Zenner and Krüger proposed the weight-shifting DPHF prop *Shifty* [63]. *Shifty* is a stick-shaped proxy that can adapt its mass distribution by shifting an internal weight with a stepper motor. *Shifty* was shown to enhance the perceived realism when rendering virtual objects of different lengths and thicknesses compared to an identical, but purely passive prop [63]. While the haptic dimension of weight distribution is most relevant to our investigated scenario, the concept of DPHF is independent of the haptic dimension. The technique has been actively studied with implementations including proxies that change their weight distribution [44, 63, 64], shape [32, 64], texture [10, 57], stiffness [38], or damped oscillation properties [54].

DPHF is a hardware-focused technique that extends passive haptics to establish *Similarity* of a proxy with multiple virtual objects in a scene. Recent considerations also hypothesized that DPHF could be employed to help tackle *Colocation* issues by compensating for unintended passive haptic sensations as a result of dislocated props [66]. In this work, we study how DPHF can be combined with the technique of Haptic Retargeting to tackle both challenges.

2.3 Haptic Retargeting (HR)

Haptic Retargeting (HR) [3,7] is a software-based technique that leverages the dominance of human visual perception [17] to tackle the challenges of *Colocation* and *Similarity*. The technique grants the VR system some control over the movements of the user's real hand. This allows the system to govern what proxy objects the user touches and where exactly the touch occurs. Conceptually, HR is closely related to *redirected walking* [39, 41, 50], a technique that manipulates users' travel through real spaces as they explore immersive VEs. While redirected walking modifies the mapping of the user's real and virtual head movements, Kohli [29] introduced the technique of *redirected touching* that offsets the virtual hand seen by the user from the real hand position. As a result of the visual dominance, a proprioceptive illusion occurs when users only see their offset virtual hand representation. This illusion in turn leads them to redirect their real hand, compensating for offsets in order to reach a destination with their virtual hand.

Kohli showed that HR can address the challenge of *Similarity* by providing feedback for differently shaped virtual objects with a proxy fixed in shape [29]. Azmandian et al. [3] further demonstrated how *Colocation* can be achieved by using HR to map a single proxy onto spatially separated virtual objects. Cheng et al. [7] extended the approach and investigated how a sparse general-purpose proxy can provide feedback for larger scenes. To realize HR, past research proposed various hand redirection algorithms ranging from *world warping* that translates or rotates the VE to align virtual objects with their proxies [3,30], over techniques that define spatial offsets (i.e. warps) across the VE [29, 37, 49, 68], to *body warping* that only locally offsets body parts (e.g. the hands) from their real positions [1, 3, 7, 18, 20, 65].

For a seamless integration of HR it is often desirable that hand manipulations are undetectable. Threshold investigations of past research have uncovered how much hand redirection is tolerated by users [7], or can even go unnoticed, e.g. in worst-case scenarios [65], when a haptic signal is present during redirection [1], when both hands are redirected [18], and when no complete hand representation is rendered [34].

In summary, HR is a technique that extends passive haptics and tackles both challenges of *Colocation*, e.g. by compensating for spatial mismatches, and *Similarity*, e.g. by redirecting to a suitable touch location. As it is based on software and perceptual illusions but independent of the proxies used, it lends itself to combination with DPHF.

2.4 Combined & Further Approaches

While a combination of DPHF and HR has, to our knowledge, not ever been practically implemented, nor have its effects on the challenges of *Similarity* and *Colocation* been studied, passive haptics, DPHF and HR have been used in combination with other techniques in the past.

Conventional passive haptics, for example, was combined with redirected walking to map multiple virtual objects in a VE onto a single proxy [30]. Steinicke et al. [51] further explored this approach and presented a taxonomy of suitable redirection techniques. Recent research [67] also combined symmetric props with resetting controllers [39] to enable prop reuse within large-scale VEs.

The hardware-focused approach of DPHF is usually combined with well-chosen visualizations to trigger various visual-haptic illusions with just a single proxy. For example, the shape-changing DPHF proxy *Drag:on* changes its surface area to adapt its air resistance in the real environment. By combining its resistance feedback with visualizations of different object scales, materials, or environmental effects, a range of visual-haptic perceptions are conveyed [64], leveraging DPHF and visual dominance effects. Similarly, the DPHF of *ElastOscillation* is combined with different visualizations to simulate either a fishing pole or the feeling of shaking a virtual fluid in a glass [54].

Abtahi et al. [2] combined HR with *encountered-type haptic feedback* to compensate for *Colocation* issues. In their system, proxies are provided just-in-time by drones as users reach out to touch and interact with virtual objects. To enable precise touching on the drone's surface, HR was employed to bridge spatial offsets as a result of drone hovering. Recently, the concept of HR has been extended to *redirected tool-mediated manipulation* to simulate contact forces that occur, for example, when driving a nail with a hammer using props in VR [52].

Beyond proxy-based approaches, techniques that solely leverage visual feedback to convey haptic effects have also been studied. Some of them produce *pseudo-haptic* perceptions, e.g. by modifying the control/display ratio [12, 24, 42, 43]. Yu and Bowman investigated pseudo-haptic rendering of mass distribution [59].

Only recently, researchers have proposed to combine DPHF and HR for enhanced haptic rendering of weight shift in VR [66]. Our work aims to verify their hypotheses experimentally, and for the first time demonstrate the practical value of combining both techniques.

3 Dynamic Passive Haptics + Haptic Retargeting

To study how dynamic proxy adaptation can act in concert with redirection of the user's hand, we chose a proof-of-concept scenario that:

1. concerns a basic and versatile haptic feedback dimension,
2. only involves low-complexity actuation and principles,
3. involves effects that can easily be observed and explained visually.

We opted for the rendering of weight distribution [44,63] as it (1) nicely aligns with these criteria and (2) has been proposed in previous research [66] to be a suitable scenario for combining DPHF and HR.

In two all-theoretical thought experiments, Zenner and Krüger recently considered potential benefits of combining DPHF and HR to improve the haptic rendering of weight shift inside a virtual stick grasped at the center [66]. These thought experiments form the motivational basis of our investigation. The authors arrive at two central hypotheses, which we aim to validate for the first time in two user experiments leveraging established perceptual experiment designs (i.e. a psychophysical method). By validating the practical feasibility of enhancing weight shift rendering by combining DPHF and HR, we aim to complement these findings of past research [66]. We show that a combination of a state-of-the art DPHF implementation (i.e. a weight-shifting prop [63]) and HR (i.e. hand redirection within unnoticeability ranges [7, 65]) enhances the haptic rendering capabilities of proxy-based VR, and that this augmentation is perceivable.

In the following, we re-introduce the scenario put forward by previous research [66], and specify the 3 rendering techniques (DPHF, HR, and DPHF+HR) that we compare in our experiments. We then define the metrics used for comparison and outline the hypotheses.

3.1 Proof-of-Concept Scenario

Our proof-of-concept scenario implements the interaction considered in the thought experiments of Zenner and Krüger [66]. The user in this scenario picks up a virtual stick represented by a tubular proxy of the exact same diameter and length. In both experiments, users see the virtual stick lying horizontally in a stand in front of them, grasp the stick at its geometric center with their dominant hand, and lift it up vertically (as shown in Fig. 1). As users hold the virtual stick, our experiments assess their perception of its weight distribution.

To perceive the weight distribution of an object in our hand, our perceptual system makes use of sensors in our muscles, tendons, and skin [55]. In this perceptual process, two physical parameters are of importance: (1) the *lever*, defined by the distance between the grasp location (i.e. where the force lifting the object acts vertically upwards) and the object's center of mass (CM) (i.e. where gravitation pulls the object downwards), and (2) the *moment of inertia*, which can be viewed as the rotational resistance defined by the distances from all of the object's individual mass elements to the hand [55, 64]. Zenner and Krüger have previously used a weight-shifting proxy to convey virtual objects varying in weight, length, and thickness. For this, they relied primarily on adaptations of the proxy's moment of inertia [63]. Our study, in contrast, will utilize a weight-shifting proxy identical in construction to investigate the *perception of balance* of a virtual stick lifted in VR.

3.2 Haptic Rendering Techniques

To convey different weight distributions in the virtual stick, we implement and compare 3 different rendering techniques (DPHF, HR, and DPHF+HR) alongside a baseline condition (BL).

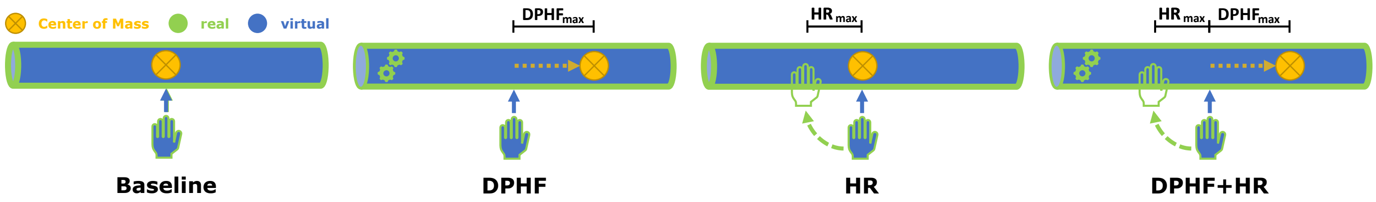

Fig. 2. The four conditions we compare. From left to right: (1) Our baseline BL is a balanced, passive proxy that does not employ any adaptation, nor haptic retargeting. (2) The DPHF technique relocates the physical CM of the proxy while a 1-to-1 hand mapping is used. (3) The HR technique redirects the real hand along the virtual stick, while the physical CM stays at the proxy's geometric center. (4) The combined DPHF+HR technique first shifts the physical CM and additionally redirects the real hand in the opposite direction to increase the lever.

3.2.1 Baseline

The baseline condition BL represents conventional passive haptics and only renders a static, balanced proxy state. It does not use any hand redirection, but only employs a 1-to-1 hand mapping, and does not involve any physical adaptation of the proxy. This condition is implemented with the weight-shifting prop introduced in the next subsection.

3.2.2 Dynamic Passive Haptics

The first actual rendering technique makes use only of a DPHF prop to convey different states of weight distribution inside the virtual stick. When the technique of DPHF is employed, the user's virtual hand is registered to the real hand movement in a 1-to-1 manner, i.e. no hand redirection is applied. Consequently, the user will grasp the proxy at the exact location where the *virtual* stick's geometric center is located.

Conceptually, for this rendering technique we assume a proxy that can dynamically locate its CM along its main axis in the range $cm \in [-DPHF_{max}, DPHF_{max}]$, with 0 being the geometric center of the prop. When the proxy is perfectly colocated with the virtual stick and its CM location is shifted to a position cm, the user experiences a lever of $|cm|$ as her hand grasps at the center location 0. Thus to render a virtual CM at location cm_{target}, the proxy shifts its internal mass in the corresponding direction to move its physical CM to cm_{target}. The maximum lever that can be achieved with DPHF in this scenario is consequently constrained by $|DPHF_{max}|$, as illustrated in Fig. 2.

To implement this technique we use the design of the weight-shifting proxy *Shifty* [63], which has been introduced in previous research. The authors of the original paper provide detailed instructions online[1] that allow for the re-creation of their DPHF proxy. *Shifty* uses a stepper motor to shift a 3D-printed mass filled with lead along its tubular acrylic body. Our implementation of the proxy is identical in construction to *Shifty* [63] and tracked with an HTC Vive Tracker on the right side, which acts as a counterweight to the motor located on the left side (see Fig. 1). Our implementation achieves $|DPHF_{max}| = 5cm$.

3.2.3 Haptic Retargeting

The HR technique does not involve any proxy actuation, but instead relies on unnoticeable hand redirection to convey weight shifts inside the virtual stick. As illustrated in Fig. 2, the technique utilizes only a passive, balanced proxy (as does the BL technique), which in our experiment is implemented by the weight-shifting proxy keeping its CM stationary at the center ($cm = 0$). When grasping the virtual stick, users will reach for its geometric center with their *virtual hand*. With HR being applied, the virtual hand is incrementally offset from the real hand position (i.e. the mapping is no longer 1-to-1), and users will compensate for these offsets by redirecting their real hand trajectory. This lets users grasp the *physical* stick at a location different from the virtual stick's center – introducing a lever.

The adaptation of the proxy's CM in the DPHF technique takes place when the user is not in contact with the proxy, and thus goes unnoticed by users. To ensure HR will also go unnoticed, the maximum range of redirection is limited by worst-case hand redirection detection thresholds derived in previous research (i.e. the real and virtual hand drift apart horizontally at an angle of 4.5° [65]). To convey a virtual CM at cm_{target}, the HR technique redirects the user's real hand to the location $grasp = -cm_{target}$ on the physical proxy to ensure the grasp location to be $|cm_{target}|$ away from the physical CM at position 0 and in the opposite direction. Constrained by the unnoticeability ranges, the grasp location on the proxy is limited to the range $grasp \in [-HR_{max}, HR_{max}]$. As a result, the maximum shift effect that can be achieved with HR is $|HR_{max}|$, as illustrated in Fig. 2.

We implement the HR technique in our experiment using the state-of-the-art body warping technique by Cheng et al. [7], which incrementally offsets the virtual from the real hand as the user reaches from an origin location (here: $60cm$ in front of the center of the virtual stick) to the retargeting destination (here: the center of the virtual stick). We use the calibration outlined in Sect. 4.3.1 and an HTC Vive Tracker attached to the back of the user's hand for tracking, as can be seen on the right in Fig. 1. Our setup yields a maximum unnoticeable redirection range along the proxy's body of $|HR_{max}| = \frac{sin(4.5°)}{cos(4.5°)} \cdot 60cm = 4.72cm$.

3.2.4 Dynamic Passive Haptics + Haptic Retargeting

The third rendering technique combines DPHF, i.e. physical relocation of the CM, and HR, i.e. the redirection of the physical hand, as follows: When rendering CM shifts up to $|DPHF_{max}|$, our combined technique applies a 1-to-1 hand mapping and relies only on DPHF, i.e. weight shifts inside the proxy, to achieve the desired lever. Only when the target lever $|cm_{target}|$ exceeds the shift capabilities of DPHF, the technique starts introducing visual real-to-virtual discrepancies by operating HR to increase the distance of the grasp location to the physical CM – effectively increasing the physical lever. This formally means that when $|cm_{target}| > |DPHF_{max}|$, the user's real hand is, in addition to the weight shift, redirected by $min(|cm_{target}| - |DPHF_{max}|, |HR_{max}|)$ (i.e. the remaining lever distance not covered by DPHF alone, capped at the maximum unnoticeable HR range). It is noteworthy that the redirection of the real hand is always in the opposite direction of the weight shift to increase the lever effect given by $lever = |grasp - cm|$. As a result, this approach theoretically achieves a maximum lever distance of $|DPHF_{max}| + |HR_{max}|$ as sketched in Fig. 2, i.e. $5cm + 4.72cm = 9.72cm$ in our implementation.

3.3 Metrics

While the theoretical benefit of combining DPHF and HR becomes apparent from aforementioned considerations, it is not yet clear if (1) these benefits are achievable in a practical implementation, nor if (2) the extension of the haptic rendering range would be perceivable with state-of-the-art implementations in use. To investigate this and study how well the four techniques handle the challenges of *Similarity* and *Colocation*, we define two metrics to compare their performance.

3.3.1 Similarity Metric

The first metric captures what it takes for a VR system to solve the challenge of *Similarity*: the ability to provide, for each interactable virtual object, a haptic experience that is most similar to what the user would expect from the interaction in reality. Mapped to our scenario, the system needs to provide convincing haptic sensations for as many different weight distributions inside the virtual stick as possible.

Thus, we regard a rendering technique that conveys a greater range of virtual CM locations as superior to a technique that cannot provide

[1] https://github.com/AndreZenner/shifty

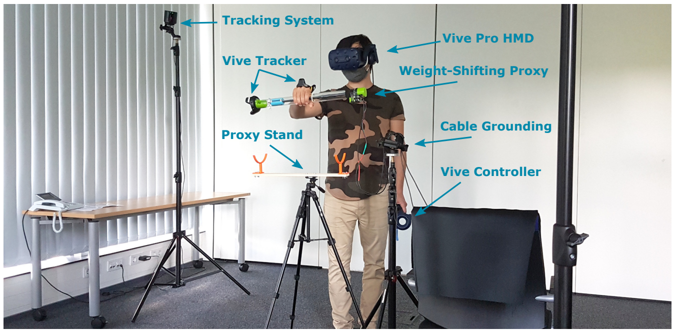

Fig. 3. Experiment setup and involved components. The cable of the proxy has been grounded with a tripod to minimize gravitational pull.

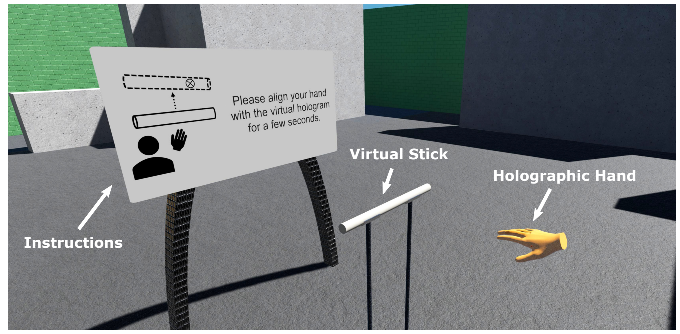

Fig. 4. View of the VE showing the instruction display and the virtual stick. Participants align their hand with the hologram to start the trial.

as large a range of CM locations. Consequently, the performance of the techniques in regard to *Similarity* is measured by $lever$ = *the maximum conveyed virtual lever*. It is given by the perceived distance of virtual CM from the grasp at the geometric center of the virtual stick.

3.3.2 Colocation Metric

Our second metric considers what it takes for a VR system to provide an optimal solution to the *Colocation* challenge. Such a solution is achieved when users can reach for any virtual object, no matter where it is located in the VE, and receive a sensation of touch that matches the way their virtual hands touch the virtual object. Transferred to our scenario, the system should provide the sensation of grasping and lifting a balanced stick for as many different virtual stick locations as possible, even if the virtual stick is spatially offset from its proxy.

We consequently regard a technique as superior if it allows for larger spatial offsets of prop and virtual stick to go unnoticed. Based on this, we gauge the performance in solving the *Colocation* challenge through off = *the maximum unnoticeable offset between proxy and virtual stick*. We restrict our investigation to offsets along the proxy's main axis, leveraging the fact that the proxy has a uniform and symmetric tubular shape. This way, users can only detect offsets by feeling an unexpected imbalance of the virtual stick when lifting it up.

3.4 Hypotheses

Based on the thought experiments discussed in previous research [66], our considerations above, and given our metrics for *Similarity* and *Colocation*, we hypothesize:

- **H1:** DPHF and HR can achieve greater perceived CM shifts than the baseline BL, and the combined technique DPHF+HR can achieve greater perceived CM shifts than both DPHF and HR: $lever(BL) < lever(DPHF), lever(HR) < lever(DPHF+HR)$
- **H2:** DPHF and HR can compensate for greater spatial offsets than the baseline BL, and the combined technique DPHF+HR can compensate for greater spatial offsets than both DPHF and HR: $off(BL) < off(DPHF), off(HR) < off(DPHF+HR)$

As $|DPHF_{max}| \approx |HR_{max}|$ in our implementation, we do not expect perceivable differences between DPHF and HR regarding both measures.

4 Evaluation

To investigate **H1** and **H2**, we conducted a user study with two experiments. The *Similarity* experiment compares the techniques with regard to the maximum weight shift they can convey. The *Colocation* experiment applies a psychometric method to capture how much the virtual stick can be offset from the proxy without users noticing it. Here, the introduced techniques are applied to prevent noticeable imbalance. The study was approved by the ethical review board responsible, and rigorous disinfection protocols were followed.

4.1 Participants

$N = 24$ (6f, 18m) participants recruited from the local campus volunteered to participate in the study, each taking part in both experiments in a counterbalanced order. Participants were from 22 years to 36 years old ($M = 26y$, $SD = 3.54y$); all had normal or corrected-to-normal vision and were right-handed. We asked participants how often they play 3D video games, use VR systems, and work with their hands on a scale from 1 (= never) to 7 (= regularly). Our set of subjects covered a wide range of experience with 3D video games ($M = 4.17$, $SD = 2.30$) and VR systems ($M = 3.50$, $SD = 2.19$), both with responses ranging from 1 to 7. Responses regarding their experience in working by hand ($M = 4.12$, $SD = 1.94$) ranged from 2 to 7.

4.2 Apparatus

Our study took place in a lab at our institution. A notebook with an NVIDIA GTX 1070 graphics card and an HTC Vive Pro HMD was used to immerse participants visually and auditorily, using a tracking system with SteamVR base stations 2.0. The dominant hand of participants was tracked using an HTC Vive Tracker (v2018) attached to the back of the hand with a rubber band. To provide answers to the questions in the VE, participants used an HTC Vive Controller in their non-dominant hand. The weight-shifting proxy used in both experiments is identical in construction to *Shifty* [63] and built according to the instructions provided by the authors online[1]. VR system and proxy communicated via WiFi and the proxy was tracked with an HTC Vive Tracker (v2018). A stand was placed in front of the participants. Including attachments, the proxy weighed $615g$ and moved the mass from end to end in $2.8s$. The impact of the weight of the cables on the proxy's left end was carefully considered when designing the experiment by (1) minimizing it through grounding with a tripod (see Fig. 3), and (2) carefully choosing the directionality of the experiment. This means that any potential effect due to cables pulling down the left end of the proxy would only act against our hypotheses and only raise the bar for validating the expected effects. Moreover, to prevent participants inferring information about the location of the weight from motor sounds, an obfuscation technique was employed. For this, the weight always moved to a random location first, before moving to its actual destination before each trial. The VE was implemented using *Unity 2019.3.7f1*, the *Unity Experiment Framework*[2] [6], and the *VRQuestionnaireToolkit*[3] [13].

4.3 Similarity Experiment

The *Similarity* experiment investigates **H1**, i.e. which of the rendering techniques conveys the strongest CM shift inside the virtual stick.

4.3.1 Procedure

After providing informed consent, each participant started with a calibration. A point on the surface of the user's palm served as the reference location for the real hand in the scene. To calibrate this point, we established the accurate offset from the tracker on the back of the hand to this point on the palm, which is in contact with the prop when grasping it. For this, participants were asked to grasp the physical stick exactly as indicated by a green holographic hand displayed in VR. A haptic

[2] https://github.com/immersivecognition/unity-experiment-framework
[3] https://github.com/MartinFk/VRQuestionnaireToolkit

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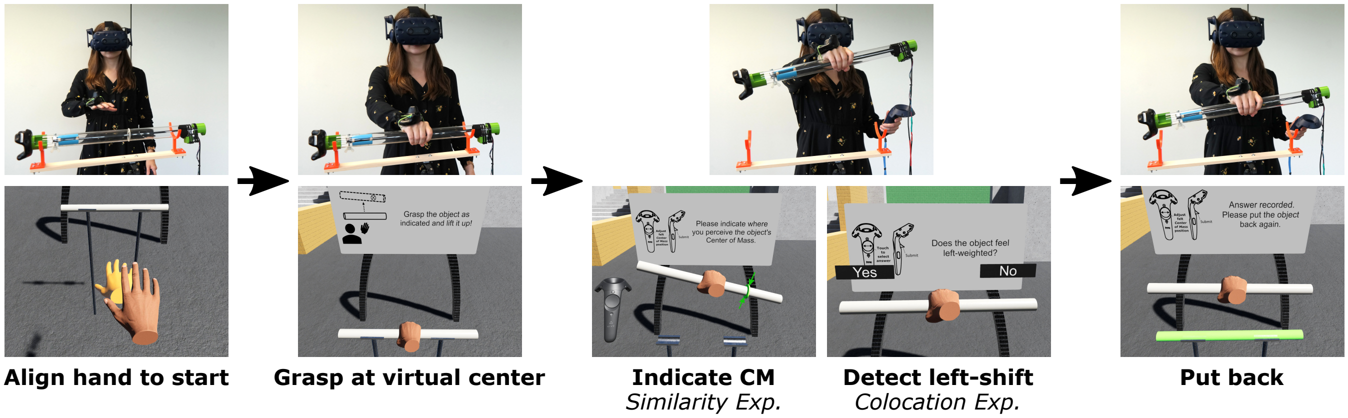

Fig. 5. Step-by-step view of an experimental trial. The user starts the trial by aligning her calibrated virtual hand with a holographic hand rendered in VR. After 2s any hand redirection applied in the trial is activated as the user starts to grasp the virtual stick at its center. The user then lifts up the stick and provides her response. In the *Similarity* experiment the user indicates the location of the perceived CM (green indicator) using the Vive controller in the second hand. In the *Colocation* experiment she answers a yes/no question asking if the stick feels left-weighted. After the answer is recorded, the trial ends by putting the object back down as indicated by the green hologram. The weight inside the proxy relocates between trials.

marker placed on the proxy surface and felt underneath the middle finger indicated correct alignment during calibration. When such correct alignment was achieved, calibration was completed and a transform representing the reference location of the real hand continued to follow the tracker with the calibrated offset for the remainder of the experiment.

Upon completion of the calibration, participants practiced in 4 training trials, before the data collection started. When training was completed, each participant performed 5 trials for each of the 4 conditions in a randomized order. To complete a trial, participants first aligned their virtual hand for $2s$ with a holographic hand in VR (see Fig. 4). This holographic hand was located at the same height as the virtual stick and $60cm$ in front of its geometric center (see leftmost VR image in Fig. 5). After $2s$, a sound signaled that the participant could now grasp the virtual stick at its center and lift it up vertically. Trials employing hand redirection would warp the virtual hand during this phase as the user's hand approached the proxy. Virtual stick and physical proxy were perfectly colocated during all trials in the *Similarity* experiment. A carefully designed grasping animation of the fingers was played when participants approached the stick to enhance immersion. After lifting up the stick, participants indicated where they perceived the CM of the virtual stick with a virtual green indicator (see center VR image in Fig. 5). To move the indicator on the stick, participants used the controller's touchpad and they recorded their answer using the trigger. When the perceived CM was recorded, participants put back the stick by aligning it with a hologram displayed in VR and retracted their hand. This flow was then repeated for the next trial, and is illustrated in Fig. 5.

After completion of all 20 *Similarity* trials, participants filled out a SUS presence questionnaire [48], a Simulator Sickness Questionnaire (SSQ) [25], were asked if they noticed their virtual hand moving differently than their real hand at any moment during the experiment, and completed additional demographic data. Upon leaving VR, participants were free to provide any further comments in a written form.

4.3.2 Design

The *Similarity* experiment has a within-subjects design. The independent variable is the haptic rendering technique with its four tested implementations (BL, DPHF, HR, DPHF+HR). Each technique was configured to render its maximum achievable lever effect towards the right end of the stick as introduced earlier and sketched in Fig. 2. Fig. 1 depicts a detailed real-world view of the conditions on the right, with the geometric center of the stick, the grasp location of the hand, and the location of the movable mass indicated.

As a dependent variable we assessed the *Similarity* metric, i.e. the perceived location of the virtual stick's CM in the continuous range $[-1, +1]$, where -1 represents the left end of the stick, 0 its center, and $+1$ the right end of the stick. Each participant completed 4 trials for training, and 20 trials with data recording (5 times each of the 4 conditions in a random order). This results in $N \cdot 20 = 24 \cdot 20 = 480$ estimates of CM locations (120 per condition) in total.

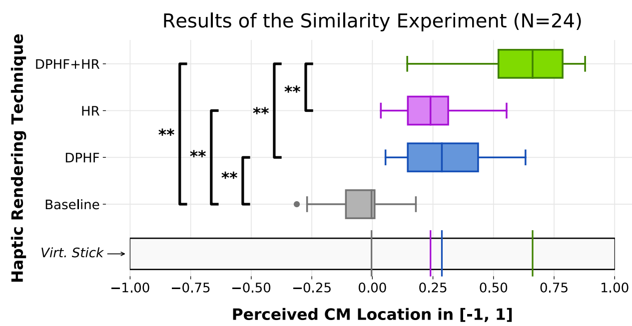

Fig. 6. Box plot of the *Similarity* results, i.e. the perceived location of the virtual CM along the stick in the range from -1 (= left end) to $+1$ (= right end) with 0 indicating the geometric center of the stick. Brackets indicate statistically significant differences ($p' < .05$ (*); $p' < .01$ (**)).

4.3.3 Results

It took participants on average $5.00s$ ($SD = .98s$) to reach for the virtual stick and lift it up, and $7.12s$ ($SD = 3.48s$) to indicate the perceived CM location. 18 participants (75%) indicated that they did not notice the hand redirection in any trial. The main results of the *Similarity* experiment are summarized in Fig. 6. To investigate **H1** and applying a significance level of $\alpha = .05$, we compared the perceived CM locations of the four conditions using SPSS. As, according to a Shapiro-Wilk test, normality could not be assumed for all conditions, we ran a non-parametric Friedman test indicating the average perceived CM location to differ significantly across conditions ($\chi^2(3) = 66.05, p < .001$). To find pairwise differences, we performed post-hoc Wilcoxon signed-rank tests (p' indicating Bonferroni-corrected p values). Except for the comparison of DPHF and HR, the average perceived CM locations of all remaining pairs were found to be significantly different (all $p' < .001$).

Most importantly concerning **H1**, we found the CM shift perceived in the BL condition ($M = -0.054$, $SD = 0.122$) to be significantly smaller than the shifts perceived with DPHF ($M = 0.295$, $SD = 0.171$) ($Z = -4.286, p' < .001, r = .62$) and HR ($M = 0.247$, $SD = 0.147$) ($Z = -4.286, p' < .001, r = .62$). The CM shift perceived when the combined technique of DPHF+HR was applied ($M = 0.611$, $SD = 0.217$) was found to be significantly larger than the shifts perceived when applying only DPHF ($Z = -4.286, p' < .001, r = .62$) or

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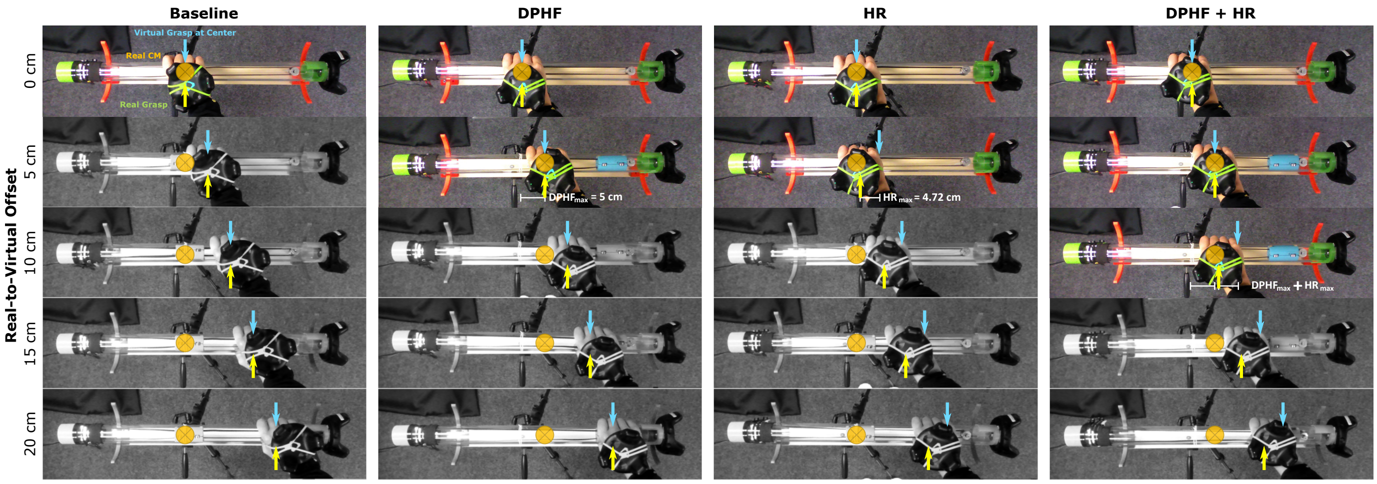

Fig. 7. The four techniques to compensate for unwanted weight shifts as a result of the dislocation of virtual stick and proxy. Blue arrows indicate the center of the dislocated virtual stick, yellow arrows show the grasp location of the real hand, and orange markers illustrate the proxy's CM for 5 representative offsets. States without a perceivable *lever* (distance yellow $\Longleftrightarrow$ orange) effect are colored; imbalanced states are black and white.

HR ($Z = -4.286, p' < .001, r = .62$). As expected, the shift ranges of DPHF and HR were not found to be significantly different ($p' = .193$).

Additionally, we computed the perceived virtual CM shifts in centimeters by mapping the range of $[-1, 1]$ to the length of the virtual stick of $59.6cm$. We then compared the perceived levers in VR to the physical levers achieved in the rendering techniques using one-sample Wilcoxon tests and a Bonferroni-Holm correction. While the perceived shift in BL ($M = -1.60cm$, $SD = 3.64cm$) was not found to be significantly different from $0cm$ ($p' = .101$), the tests revealed that users significantly overestimated weight shifts in VR (given by *lever*):

$$\begin{aligned} lever(HR) &= 7.37cm \overset{p'<.028}{>} 4.72cm = |HR_{max}| \\ lever(DPHF) &= 8.78cm \overset{p'<.012}{>} 5.00cm = |DPHF_{max}| \\ lever(DPHF+HR) &= 18.20cm \overset{p'<.004}{>} 9.72cm = |(DPHF+HR)_{max}| \end{aligned}$$

Finally, the results of the presence questionnaire for the SUS count ($M = 2.21$, $SD = 1.86$) (with answers ranging from 0 to 6), and SUS mean ($M = 4.72$, $SD = 1.22$) confirm the VE to be sufficiently immersive. Participants did not report any cybersickness issues, as is supported by the obtained SSQ total scores ($M = 26.96$, $SD = 19.01$).

4.4 Colocation Experiment

The *Colocation* experiment studies **H2**, i.e. which technique compensates best for unwanted CM shifts when the virtual object is dislocated from its proxy. For this, we utilize a psychophysical method to derive, for each technique, its detection threshold of real-to-virtual offsets.

4.4.1 Procedure

Just like in the *Similarity* experiment, participants started by completing the hand calibration procedure and a set of training trials, before data collection started. From the perspective of participants, the trials in the *Colocation* experiment were equivalent to those in the *Similarity* experiment, except for the question. In the *Colocation* experiment, participants were asked in each trial whether the virtual stick felt *left-weighted*, i.e. heavier on the left side, or not. Participants did not need to indicate the perceived CM location as in the *Similarity* trials, but only answered the yes/no question using the controller (see Fig. 5). A second difference from the *Similarity* experiment is that in the *Colocation* experiment, the proxy and the virtual stick were not always perfectly colocated, but the virtual stick's center was offset in each trial by a *stimulus* $\in [0, 20cm]$ towards the right from the physical stick's center. This stimulus was controlled by an interleaved staircase procedure as introduced in the following subsection. While users could only see the virtual stick and were instructed to grasp it at its center, the haptic rendering techniques were used to compensate for unwanted physical lever effects caused by these dislocations. Fig. 7 depicts a detailed overview of how the techniques compensate for various amounts of real-to-virtual offsets. The illustration indicates the grasp location of the virtual hand, i.e. the center of the displaced virtual stick, with a blue arrow. The physical CM location is shown in orange, and the virtual grasp location in green and observable from the hand in the pictures. After completing an interleaved staircase procedure for each of the four tested conditions, participants were asked to fill out the same questionnaires as in the *Similarity* experiment.

4.4.2 Design

The *Colocation* experiment has a within-subjects design, with the independent variable being the technique employed to compensate for unwanted weight shifts caused by the dislocation of the virtual and physical stick (BL, DPHF, HR, DPHF+HR). An estimation of the *maximum unnoticeable offset* of the virtual stick and its proxy along the stick's main axis serves as the dependent variable. This offset detection threshold represents the *Colocation* metric and was determined by employing an adaptive method from the field of psychophysics – an *interleaved staircase procedure* [26]. Formally, we applied a 1 up/1 down method with a fixed step size and two interleaved sequences ($\Delta^+ = \Delta^- = 2cm$; min. stimulus of $0cm$; max. stimulus of $20cm$) [27].

The staircase procedure varied the offset of the virtual stick's geometric center from the center of the proxy (i.e. the *stimulus*) across trials. It operated with an ascending sequence (plotted in red in Fig. 8) starting at no offset, and a descending sequence (plotted in blue in Fig. 8) starting at the maximum offset of $20cm$. Each trial was randomly assigned to one of the sequences and when a stimulus was noticed in a trial (i.e. the participant answered that she noticed that the virtual stick felt imbalanced), the offset for the following trial was decreased by the fixed step size of $2cm$. If, in a trial, the participant failed to notice a stimulus (i.e. the haptic technique was successful in compensating for any perceivable lever effect, and the virtual stick was perceived as balanced), the offset in the following trial of that sequence was increased by $2cm$. If in one trial of a sequence the participant noticed an imbalance, while in the preceding trial she did not (or vice versa), the sequence logged a reversal. Each sequence was progressed until 5 reversals had occurred, out of which the last 4 reversals were averaged to estimate a threshold for the respective sequence. Finally, the average of the ascending and descending sequence thresholds was taken as a general offset detection threshold estimate for each participant. The threshold indicates how much dislocation can go unnoticed with the tested technique being used to compensate for undesired weight shifts.

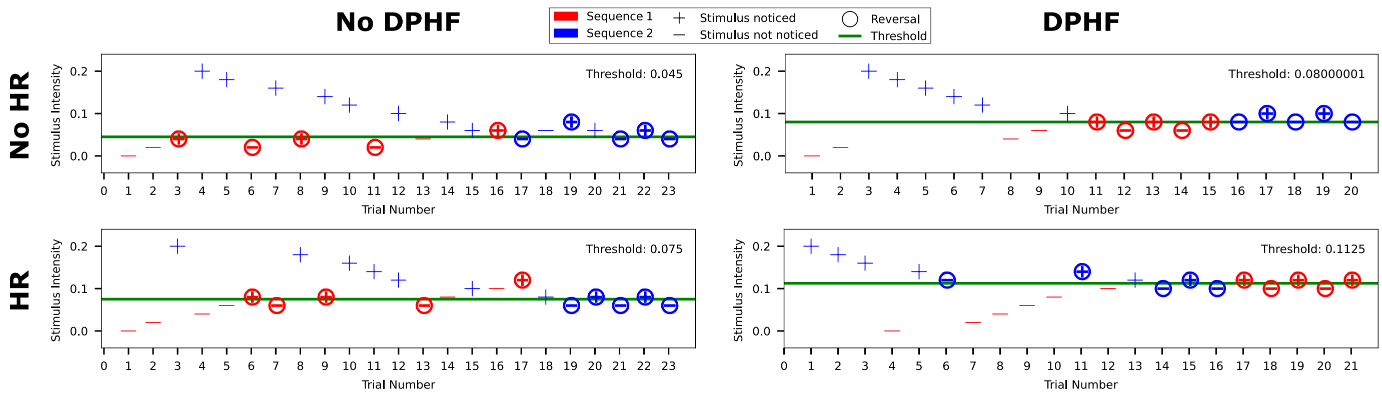

Fig. 8. Interleaved staircase results from participant #16 in the *Colocation* experiment for all four conditions. The *stimulus* on the y-axis represents the offset of the virtual stick's center from the center of the proxy in meters. The offset detection thresholds that can be observed are in line with **H2**.

Each participant completed an interleaved staircase procedure for each of the 4 tested conditions. A 4x4 Williams design Latin square [58] was used to counterbalance the order of conditions across participants.

4.4.3 Results

It took participants in the *Colocation* experiment on average $5.28s$ ($SD = 3.91$) to reach for the virtual stick and lift it up. The yes/no question was answered on average within $2.94s$ ($SD = 1.39$). 21 participants (87.5%) failed to notice the hand redirection during the experiment. Fig. 9 summarizes the central results of the *Colocation* experiment. To arrive at these threshold estimates, which indicate the maximum offset of proxy and virtual stick that the techniques can compensate for in meters, a total of 2218 trials was conducted across all participants. On average, each participant completed 92.42 trials ($SD = 6.48, max. = 109, min. = 84$).

To investigate **H2**, we applied a significance level of $\alpha = .05$ and compared the offset detection thresholds of the four techniques using SPSS. A Shapiro-Wilk test indicated that normality could not be assumed for each condition and a Friedman test signaled the thresholds to vary significantly across techniques ($\chi^2(3) = 61.08, p < .001$). Post-hoc analysis with Wilcoxon signed-rank tests and Bonferroni correction revealed all pair-wise comparison of thresholds to be significantly different (all $p' < .001$), except for the comparison of DPHF and HR. Most meaningful regarding **H2**, the offset detection threshold when no compensation for undesired weight shifts is applied in BL ($M = 3.95cm$, $SD = 2.19cm$) was found to be significantly smaller than when DPHF ($M = 7.13cm$, $SD = 2.95cm$) ($Z = -4.286, p' < .001, r = .62$) or HR ($M = 6.74cm$, $SD = 2.55cm$) ($Z = -4.199, p' < .001, r = .61$) was used for compensation. Moreover, the combined technique DPHF+HR was found to compensate for the most spatial offset, with detection thresholds ($M = 10.13cm$, $SD = 2.99cm$) found to be significantly larger than when using only the individual techniques of DPHF ($Z = -4.076, p' < .001, r = .59$) or HR ($Z = -4.286, p' < .001, r = .62$). As expected, the thresholds of DPHF and HR were not found to differ significantly ($p' > .99$).

Interpreting these values, the BL threshold can be viewed as the user's general 'tolerance' for CM offsets. Based on this consideration, we computed, for each rendering technique, its actual contribution to the increased tolerance for real-to-virtual offsets by subtracting the BL threshold (participant-wise). We then compared the contribution of DPHF+HR ($M = 6.19cm$, $SD = 1.69cm$) to the sum of the contributions of the individual techniques DPHF and HR ($M = 5.98cm$, $SD = 1.83cm$). A Wilcoxon signed-rank test did not find the difference ($\Delta = 0.21cm$) to be statistically significant ($p = .853$).

Just as in the *Similarity* experiment, the SUS count ($M = 2.37$, $SD = 1.95$) (with responses from min. 0 to max. 6), SUS mean ($M = 4.79$, $SD = 1.27$), and SSQ total scores ($M = 34.75$, $SD = 25.18$) confirmed the VE to be generally immersive and free of sickness issues.

Fig. 9. Box plot of the offset detection threshold in meters as estimated by the staircase procedure in the *Colocation* experiment. It is the maximum offset of virtual stick and proxy that goes unnoticed. Brackets indicate statistically significant differences ($p' < .05$ (*); $p' < .01$ (**)).

5 Discussion

We found that DPHF+HR can be superior to the individual techniques when it comes to solving the *Similarity* and *Colocation* challenges.

5.1 Enhancing Similarity

Our *Similarity* results are in line with the hypotheses derived in Zenner and Krüger's thought experiments [66]. A comparison of the shifts conveyed with the three rendering techniques to the baseline perception verifies the general effectiveness of DPHF, HR, and DPHF+HR in rendering virtual mass distribution. All three conditions generated significantly stronger shift perceptions than BL. Moreover, the shifts achieved with the combined technique DPHF+HR were significantly greater than those conveyed with DPHF and HR alone. The lever effect perceived with DPHF+HR ($M = 18.20cm$) even exceeded the sum of those perceived with DPHF and HR ($M = 16.16cm$) – although not significantly, according to a Wilcoxon signed-rank test ($p = .11$).

In general, our findings verify (1) that we could successfully combine both techniques in practice to improve the haptic rendering capabilities of the VR system, and (2) that the benefits of combining DPHF and HR are perceivable with state-of-the-art implementations (i.e. a weight-shifting prop like *Shifty* [63] and Cheng et al.'s body warping [7]). Based on our results, we accept **H1**, and provide a first proof of the capacity of combining proxy adaptation and hand redirection.

We also found that users tend to overestimate CM shifts in VR. The perceived virtual shifts were significantly greater than what one would expect given the physical levers produced. The overestimation affected all rendering techniques, with similar ratios of *perceived virtual* to *rendered physical lever* (1.56 for HR, 1.76 for DPHF, 1.87 for DPHF+HR) – a finding worth exploring in future studies. This indicates that techniques that are only capable of producing small ranges of shift effects can still convey larger effects in VR. Moreover, this tendency to overestimate virtual weight shifts highlights the utility of our combined approach, as every extension of the rendering range results in an even larger extension of the range of virtual shifts conveyed. The way in which this overestimation is linked to the general performance of humans in estimating the CM remains to be explored in future work.

Our findings transfer directly to applications that employ proxy-based haptics and render virtual mass distribution. In such applications, our combined technique allows a single proxy to convincingly represent a greater variety of virtual objects – e.g. a balanced virtual stick, a shovel, a sword, or a hammer – while maintaining *Similarity*.

5.2 Enhancing Colocation

The *Colocation* results complement our findings regarding *Similarity*, and also align with the hypotheses of previous research [66]. We presented how haptic rendering of weight shifts can help solve *Colocation* issues in proxy-based VR. For this, we used the rendering techniques to cancel out undesired lever effects, which can be a result of spatial mismatches of virtual object and proxy. The offset detection thresholds obtained in the BL condition represent the general tolerance for misaligned real and virtual CMs, and indicate how much the proxy in our scenario can be dislocated before the misalignment is noticed. As highlighted by the significantly increased thresholds achieved with DPHF, HR, and DPHF+HR, compensation for such CM offsets yields a larger range of unnoticeable dislocation – i.e. better solves the *Colocation* challenge. Additionally, we found DPHF+HR to achieve a range of unnoticeable dislocation that significantly exceeds the ranges obtainable with just DPHF or unnoticeable HR. The additional range contributed by DPHF+HR to the threshold closely matched the sum of the individual contributions of DPHF and HR, which coincides with the theoretical model [66] and demonstrates the practical realizability. Based on this evidence we also accept **H2**. Moreover, our observation that 75% and 87.5% of participants in the *Similarity* and *Colocation* experiments, respectively, failed to notice the hand redirection supports the detection thresholds found by previous research [65].

It is worth noting that this improved solution of the *Similarity* and *Colocation* challenges came at no additional hardware costs compared to a DPHF solution, as the same proxy was used. The only expense to improve the haptic rendering is the added complexity to implement hand redirection, and to orchestrate any interactions with virtual objects. In practical implementations, our combined technique can be utilized to let a single dynamic prop represent a set of virtual objects that are spatially dislocated in VR. As long as they are within the unnoticeability range, users can remain unaware that they are all represented by the same proxy – solving the *Colocation* challenge for such cases.

5.3 Beyond the Proof-of-Concept Scenario

Our proof-of-concept scenario was chosen to propose the idea of combining DPHF and HR. The physical laws of mass distribution make this scenario perfectly suitable to study and showcase the concept. Moreover, it is of general importance when it comes to creating believable VR experiences, as can be seen from the increasing research interest in rendering virtual mass distribution [16,44,59,63]. However, we believe both concepts can also be combined when rendering other effects.

For example, DPHF proxies that can change their surface textures by relocating surface samples (like the *Haptic Revolver* [57], or the *Haptic Palette* [10]) could benefit from simultaneous hand redirection to increase the amount of samples that can be explored. In other scenarios, such as when leveraging air drag to render resistance effects in VR (as implemented by the *Drag:on* proxy [64]), gain-based hand redirection could modify the user's hand movement speed to intensify the perceived air resistance. Altering hand movement speeds while interacting with a controller such as *ElastOscillation* [54] could likewise yield novel effects of elasticity. DPHF props rendering different degrees of stiffness [38] could potentially benefit from a combination with HR too, e.g. by redirecting the hand as the user explores the prop surface, or by applying gain factors when the proxy is squeezed. Moreover, while our experiments only employed conservative HR within worst-case unnoticeability ranges [65], future implementations might take advantage of larger HR ranges, which might go unnoticed in less conservative applications, or lie within tolerance thresholds [7].

The exact way in which DPHF and HR can best be combined in order to enhance haptic rendering in VR depends on the physical laws underlying the targeted haptic effects. For the rendering of CM shifts, these laws are straightforward and primarily concern increasing or decreasing the lever distance. For other haptic dimensions, we would like to motivate future research to find effective approaches.

5.4 Limitations

Our investigation showed the value of DPHF+HR in the context of our proof-of-concept scenario and in terms of the *Similarity* and *Colocation* metrics defined in Sect. 3.3. The benefits reported in our experiment, however, only hold under certain assumptions (e.g. we assumed the dislocation of the prop to only take place along the prop's main axis), and we could only investigate a single haptic dimension (i.e. weight shift) represented by a single implementation (i.e. used weights and dimensions) in our experiments. As a consequence, the metrics, principles, and algorithms applied here, while likely generalizable to haptic effects that have similar physical laws involved, probably do not work as-is for every imaginable haptic dimension or prop form factor. With this first step towards a rigorous scientific analysis of the value of combining DPHF and HR, however, we regard these limitations as motivation for future research – especially in light of the promising findings uncovered in the investigated proof-of-concept scenario.

6 Conclusion & Future Work

This paper presents a first realization of a VR system that combines two techniques, which enhance proxy-based haptics in VR, and which have been studied only independently in the past: Dynamic Passive Haptic Feedback (DPHF), i.e. proxies that adapt their physical state through actuation, and Haptic Retargeting (HR), i.e. hand redirection techniques that take advantage of proprioceptive illusions. We showed in a proof-of-concept scenario how both techniques can be successfully combined in theory and in practice. Based on previous research [35, 52, 66], which formulated criteria for successful proxy-based haptics for VR, we defined two metrics for the two central criteria of *Similarity* and *Colocation*. Our metrics consider the capacity of rendering mass distribution inside a virtual stick, and we argue based on these metrics that the combined DPHF+HR technique can provide feedback that is superior to the feedback provided by the individual techniques. Specifically, we hypothesized that when combining DPHF and HR to render weight shifts, the combined technique DPHF+HR will provide significantly greater perceived shifts (**H1**) and allow for significantly greater spatial offsets of virtual stick and physical proxy to go unnoticed by compensating for larger mismatches in CM location (**H2**). In a perceptual and a psychophysical experiment, we showed that the hypothesized effects can be achieved using a state-of-the-art weight-shifting proxy and hand redirection algorithm. Our statistical results led us to accept both **H1** and **H2**, and we additionally obtained evidence that users overestimate weight shifts in VR significantly. In conclusion, we provide a first systematic study of how DPHF and HR can act in concert to enhance a VR system's proxy-based haptic rendering capabilities, and our results strongly motivate continuing this research endeavor in the future.

We encourage researchers to continue investigating how dynamic proxies and haptic retargeting can form a symbiosis, e.g. by exploring multi-purpose DPHF concepts that target other form factors and haptic dimensions such as texture, stiffness, shape, resistance, or elasticity, generalizing our findings. We also plan to examine the observed overestimation of virtual weight shift in follow-up experiments. Ultimately, we aim to derive a set of requirements that VR systems need to meet in order to profit from combined DPHF+HR techniques.

Acknowledgments

The authors wish to thank David Liebemann, Sören Klingner, and Marc Ruble for their support in preparing the experiment, as well as all participants of the study. This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 425868555; 450247716.

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