# Haptic Proxies for Virtual Reality: Success Criteria and Taxonomy

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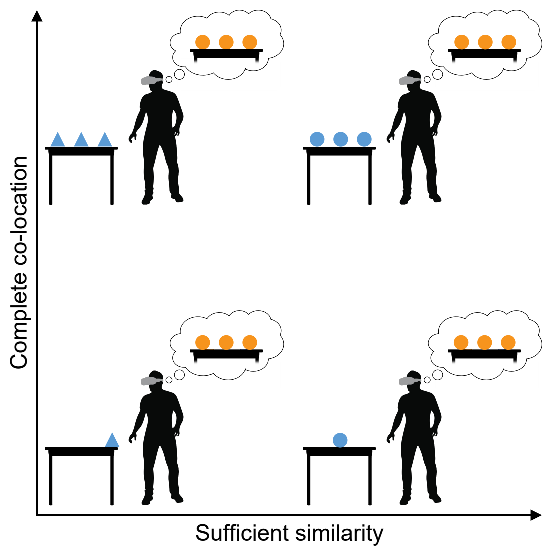


**Figure 1: Visualization of the two orthogonal criteria for successful use of haptic proxies in VR: sufficient similarity and complete co-location. Haptic proxies are highlighted with blue and virtual objects with orange.**

## ABSTRACT

In this position paper we discuss three criteria for successful use of haptic proxies in virtual reality, present a taxonomy of techniques using haptic proxies, and argue that it is only a subset of these techniques that are useful when relying on everyday items as haptic proxies.



## CCS CONCEPTS

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

## KEYWORDS

virtual reality, haptic proxies, physical props

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# 1 INTRODUCTION

Physical props serving as proxies for virtual objects (*haptic proxies*) offer a cheap, convenient, and compelling way of delivering kinesthetic, proprioceptive, and cutaneous feedback to users immersed in virtual reality (VR). In this position paper, we discuss three criteria for successful use of haptic proxies in VR, we present a taxonomy of techniques relying on haptic proxies, and we discuss the utility of these techniques when it comes to relying on everyday objects as haptic proxies.

# 2 SUCCESS CRITERIA FOR HAPTIC PROXIES IN VR

Most benefits of using haptic proxies as a source of touch in VR can be attributed to the fact that users interact with physical objects. Physical objects eliminate the need for simulating material and geometric properties, such as texture, hardness, weight, shape, and size. However, the limitations of haptic proxies are also imposed by the use of physical objects. The utility of haptic proxies decreases in proportion to the complexity of the virtual environment (VE). As VEs grow more complex, a larger number of haptic proxies with different material and geometric properties is needed. As we have argued elsewhere [18], these constraints make it useful to consider at least three high-level criteria for successfully deploying haptic proxies in VR:

(1) **Sufficient similarity:** All haptic proxies touched by the user should be sufficiently similar to their virtual counterparts with respect to their haptic properties (e.g., shape, size, and weight).
(2) **Complete co-location:** When the user touches a virtual object, it should be co-located with a haptic proxy (i.e., the real and virtual transformations should be aligned).
(3) **Compelling contact forces:** If the user touches a virtual object affected by contact forces originating in the VE, then compelling stimuli should be provided (e.g., stimuli representing forces produced by impacts or resistance).

Notably, the criteria of sufficient similarity and complete co-location are orthogonal, as it is possible to satisfy one without satisfying the other. For example, a subset of the virtual objects may be co-located with perfect physical replicas, or all virtual objects may be represented by physical props that are not sufficiently similar to their virtual counterparts (see Figure 1). Contrarily, the criterion of compelling contact forces is not independent of the other criteria. If both sufficient similarity and complete co-location are perfectly satisfied (e.g., if the VE and the physical environment are perfect copies), then all interactions between a grasped virtual object and the VE, will be accompanied by contact forces resulting from the interaction between the corresponding physical objects. However, it is usually only possible to achieve perfect similarity and co-location in relation to very simple VEs offering limited interactions. Thus, it is relevant to treat compelling contact forces as a separate criterion in relation to many virtual scenarios.

Finally, the degree to which the three criteria need to be satisfied is likely to vary depending on the type of VR application. For example, some VR training applications may demand perfect realism to ensure skill transfer, whereas the requirements may be relaxed somewhat in relation to some entertainment applications, especially if the virtual scenario does not abide by the rules of physical reality [16].

# 3 TAXONOMY AND RELATED WORK

The taxonomy divides techniques relying on haptic proxies into four broad categories based on how they address one or more of the three criteria outlined in the previous section. The categorization is based on two dichotomous categories pertaining to two orthogonal dimensions. First, we distinguish between techniques based on *what* reality is being manipulated. Is the *physical* or *virtual* environment being manipulated? Second, we distinguish between techniques based on *when* the manipulation occurs. Is the manipulation performed *offline* before the user is exposed to the VE or *real time* during exposure? Figure 2 visualizes the taxonomy, which we describe in more detail throughout the following.

## 3.1 Offline Physical Manipulation

Haptic proxies can be deliberately made to replicate virtual objects or VEs. For example, Insko et al. [11] physically replicated a simple interior VE using wooden boards and Styrofoam walls. One of our previously studied systems incorporated physical props designed so as to allow for the interaction with virtual objects inside a VR application for immersive data exploration [29]. Work involving physical replication is often limited to relatively simple tasks that only require interaction with a single virtual object [8]. Moreover, recent work has sought to automatize the design and construction of proxies approximating the properties of virtual objects without the need for near-perfect physical replicas [7, 9, 31].

## 3.2 Offline Virtual Manipulation

Offline virtual manipulation implies that virtual objects and VEs are modelled to match the physical environment before the application is run. This approach addresses the criteria of sufficient similarity or complete co-location, at the expense of virtual variety and complexity. Simeone et al. [16] proposed that for some applications it is sufficient to virtually replicate the layout of the physical environment without perfectly replicating all virtual objects (e.g., the bridge of a space ship may be modelled to fit a living room and a torch may serve as a proxy for a lightsaber). Such *Substitutional Realities* give developers a larger degree of freedom since the criterion of sufficient similarity is relaxed somewhat. Similarly, Sra et al. [17] showed that the layout of physical environments can serve as the basis for large procedural generated VEs, which can be navigated on foot as long as the VEs include barriers that restrict virtual movement.

## 3.3 Real-Time Physical Manipulation

Because head-mounted displays (HMDs) deprive users of visual information about the physical environment, this environment can be manipulated during runtime. Robotic arms can be used to ensure correct positioning of haptic proxies with varying textures [1]; thus addressing both the criteria of sufficient similarity and complete co-location. Drones have been used in a similar manner to enable direct interaction with virtual objects [10] and to enable compelling contact forces when interaction is performed indirectly

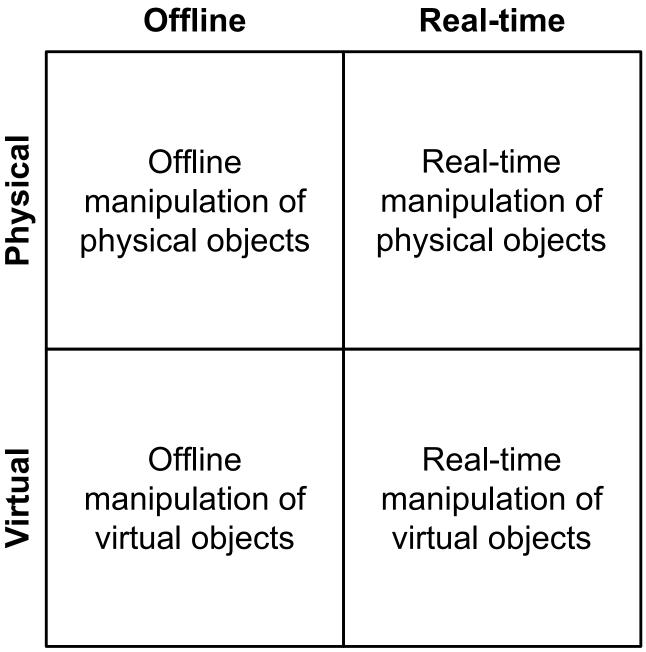


**Figure 2: Taxonomy for categorizing techniques using haptic proxies in VR. The vertical axis subdivides the techniques based on *what* reality is being manipulated (physical or virtual), and the horizontal subdivides the techniques based on *when* the manipulation is performed (offline or real-time).**

[23]. Moreover, approaches such as the *iTurk* [5] subtlety force users to reconfigure haptic proxies so they can serve as a proxies for different virtual objects. Zenner and Krüger [25] proposed *Dynamic Passive Haptic Feedback* which involves augmenting physical props with mechanical actuators to modulate haptic perception. For example, the *Shifty* [25] changes the prop's internal weight distribution to manipulate the inertia experienced when handling different objects, and *Drag:on* [26] changes the haptic proxy's surface area to elicit the impression of interacting with objects with varying scales, materials, and fill states. Moreover, physical props augmented with vibrotactile actuators can be used to approximate contact forces during virtual impacts [8, 22].

### 3.4 Real-Time Virtual Manipulation

Visual dominance makes it possible to subtly affect haptic perception by manipulating the VE or users' virtual bodies when they are wearing a HMD. Sufficient similarity can be addressed using *Redirected Touching* [12] and *Resized Grasping* [4], which warps the mapping between users' real and virtual hand and finger movements to enable virtual objects of different shape or size to be mapped onto a single haptic proxy. To ensure complete co-location, walking users can be repeatedly steered back to the same haptic proxies through *Redirected Walking*, which manipulate either the mapping between the users' real and virtual movements [13] or the virtual architecture [19]. Complete co-location of objects in peripersonal space has been addressed in a similar manner by warping VEs, users' virtual arms, or both using *Haptic Retargeting* [3]. Moreover, change blindness can be leveraged to remap virtual objects onto haptic proxies behind users' backs [14], and redirected touching has been combined with two haptic proxies (a tool and a surface) to provide compelling contact forces during tool-mediated interaction in VR [18]. To support researchers and developers in crafting solutions that employ haptic retargeting, we recently proposed an open-source hand redirection toolkit [24]. Similar efforts were taken by the redirected walking research community with the publication of a toolkit for redirected walking [2].

### 3.5 Combining Techniques of Different Categories

The combination of techniques from different categories is not excluded and bears great potential [28]. In recent research that investigated the scenario of haptically conveying the weight distribution of a virtual object, we could demonstrate and validate the benefits of combining real-time physical and real-time virtual manipulation. In this scenario, a technique that combined a weight-shifting proxy (i.e. real-time physical manipulation in the form of dynamic passive haptics) and haptic retargeting (i.e. real-time virtual manipulation in the form of hand redirection) was compared to the individual techniques. The results highlight that the combination of both concepts can better solve the challenges of similarity and co-location than the individual techniques alone can do [28, 30].

## 4 EVERYDAY HAPTIC PROXIES FOR VR

As evident from the previous section, recent years have seen increasing interest in the use of haptic proxies as a means of delivering virtual touch. Nevertheless, it is worth questioning the utility of some of these techniques if everyday items are to be integrated in virtual experiences. Everyday settings, such as homes, workplaces, or schools, impose additional restrictions and present novel challenges.

*Offline physical manipulation* is tantamount to the creation of haptic proxies based on the objects present in the VE. Because most everyday items cannot be physically manipulated, the utility of offline physical manipulation is limited. However, a small selection of everyday items may be subject to offline physical manipulation. For example, the *HapTwist* [31] makes it possible to use the same reconfigurable toy (Rubik's Twists) as a haptic proxy for multiple virtual objects.

On the other hand, *offline virtual manipulation*, such as Substitutional Reality, may achieve acceptable levels of co-location and similarity. However, the design space for Substitutional Reality remains relatively unexplored [15]. Even though a growing body work has explored the extent to which users will tolerate mismatches between real and virtual objects and how varying levels of discrepancy affect behavior and performance [4, 6, 8, 16, 22, 27], these effects are not fully understood, and it remains uncertain how they vary across applications demanding different levels of realism. It it is still difficult to dynamically generate VEs from physical environments, and it is not straightforward to differentiate between objects that can be used for interaction and the background VE. Finally, there is a need for authoring tools enabling creation of virtual content that can be meaningfully deployed across varying physical environments.

Concerning *real-time physical manipulation*, the use of everyday items is still constrained by the limited ability to modify and augment them with fragile mechanical parts. However, it is conceivable that everyday items can be augmented relatively easily with simple vibrotactile actuator modules, which can be used to manipulate perception of haptic properties and approximate contact forces during virtual interactions. Recent research also started to explore how everyday robots could ensure co-location in proxy-based VR scenarios [20, 21]. Moreover, approaches relying on human actuation, such as the *iTurk* [5], could be used to subtly repurpose everyday haptic proxies.

The techniques belonging to the category *real-time virtual manipulation* are perhaps the most promising in relation to everyday haptic proxies. Specifically, because the manipulation is entirely virtual, there are no limits to what everyday items can be incorporated into the VE. Furthermore, these approaches can be combined with Substitutional Realities to enable incorporation of the entire everyday setting while allowing for interaction with a larger number of virtual objects with varying haptic properties. The availability of open-source software toolkits for hand redirection [24] and redirected walking [2] have potential to lower the barriers for developers and researchers to experiment with integrating everyday proxies in VR. However, in an everyday setting, real-time virtual manipulation also necessitates dynamic generation of virtual content from physical environments, and several of these approaches are contingent upon information about what objects the user will interact with next. This introduces the need for highly specific scripted scenarios or the ability to reliably predict users' behavior.

Finally, it is unlikely that any one approach will be able to simultaneously ensure sufficient similarity, complete co-location, and compelling contact-forces. Thus, it is necessary for future work to explore how different techniques can be combined dynamically based on information about the state of physical and virtual environments and the users' current and future actions.

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