Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences

Adalberto L. Simeone[†*]
adalberto.simeone@port.ac.uk

Eduardo Velloso[*]
e.velloso@lancaster.ac.uk

Hans Gellersen[*]
h.gellersen@lancaster.ac.uk

[†]University of Portsmouth
Portsmouth, United Kingdom

[*]Lancaster University
Lancaster, United Kingdom

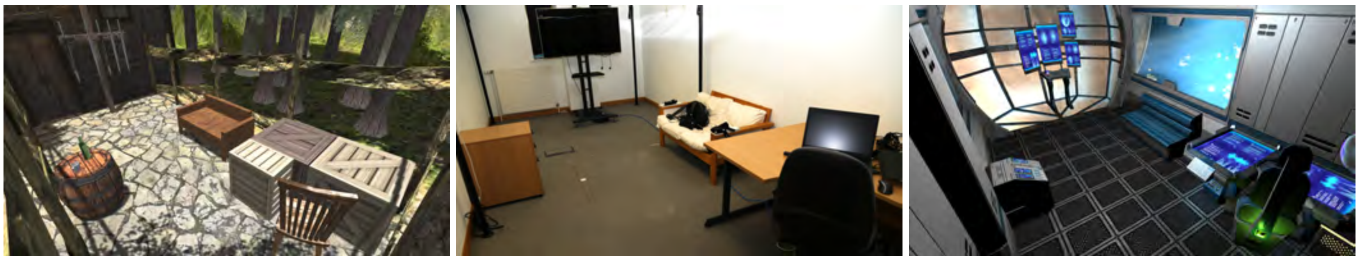

Figure 1. Two Virtual Environments based on the layout of a real room (middle): a medieval courtyard (left) and the bridge of a spaceship (right). In these *Substitutional Environments*, every physical object is paired, with some degree of discrepancy, to a contextually appropriate virtual object.

ABSTRACT
Experiencing Virtual Reality in domestic and other uncontrolled settings is challenging due to the presence of physical objects and furniture that are not usually defined in the Virtual Environment. To address this challenge, we explore the concept of Substitutional Reality in the context of Virtual Reality: a class of Virtual Environments where every physical object surrounding a user is paired, with some degree of discrepancy, to a virtual counterpart. We present a model of potential substitutions and validate it in two user studies. In the first study we investigated factors that affect participants' suspension of disbelief and ease of use. We systematically altered the virtual representation of a physical object and recorded responses from 20 participants. The second study investigated users' levels of engagement as the physical proxy for a virtual object varied. From the results, we derive a set of guidelines for the design of future Substitutional Reality experiences.

Author Keywords
Virtual Reality, Substitutional Reality, Passive Haptics

ACM Classification Keywords
H.5.1 Information Interfaces and Presentation: Artificial, augmented and virtual realities

INTRODUCTION
Virtual Reality (VR) has been applied in many contexts, including: archaeology, industrial design, training, therapy, and gaming. Despite a renewed commercial interest [14], its adoption in the home environment has been slow to take off. In contrast to VR laboratories, domestic spaces are filled with furniture and objects that may not be present in a simulation. As a consequence, home VR is constrained to the user's immediate surroundings. We envision a VR experience that incorporates physical objects into the virtual world by using them to represent objects relevant to the virtual context. We call this type of experience *Substitutional Reality* (SR) [24].

In an SR environment, every physical object and architectural feature is replaced in the Virtual Environment (VE) by a counterpart. This leverages the physicality of the real world to provide tangibility to virtual objects and contributes to a higher sense of presence [7]. For example, a living room can be substituted with a courtyard or the bridge of a spaceship (see Figure 1) and a suitable physical object (e.g., a torch or umbrella) can be replaced by a sword or a lightsaber.

Previous research has focused on scenarios where the virtual object is modelled on the physical proxy. However, to give content authors creative freedom and flexibility in the design of virtual worlds, SR experiences should be designed around the idea that a mismatch between virtual elements and their physical proxy is to be expected. In this work, we explore the question of how far designers can push this mismatch before breaking the VR illusion. Our approach builds on the concept of *passive haptics* [7], i.e. receiving feedback from touching a physical object that is registered to a virtual object.

We propose a multi-layer model of substitution which illustrates increasing levels of mismatch between the virtual counterpart and the physical object. At the bottom level, the substituted object is simply a replica of the original one. At the top level, the appearance of a substituted object has few, if any, connections to the appearance and function of the phys-

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ical one. We investigate the impact of this mismatch on the user experience in the VE through two studies.

In the first, we focused on a single baseline object, a real mug, and systematically presented participants with virtual objects representing the different types of substitution defined in the model. Our goal was to explore which factors have the greatest impact on the believability of the experience. In the second, we took the inverse route. We asked participants to hit a moving target with a virtual Lightsaber. However, the physical objects they held changed between a 1:1 Lightsaber replica, an umbrella, and a torch. We investigated those scenarios in which the user is required to interact with objects that might be common in the context of the SR experience (e.g., historical or imaginary objects) but are rarely found in homes. Our goal was to evaluate whether different objects (that can be manipulated similarly to the virtual one) can provide comparable levels of engagement to actual replicas.

Results from our studies show that, in the absence of exact replicas, those objects that present similar affordances [5] in the parts most likely to be interacted with, are the best candidates for substitution. For example, a torch for a Lightsaber or a pen for a magic wand. We found that the believability of the pairing is affected by the material used by the virtual counterpart. Those with variations in their tactile feedback, temperature, or weight had the most impact. However, participants found moderate mismatches (an oil lamp for a real mug) to be believable and with little impact on the experience. Pairings having extreme mismatches (a box for a real mug) were found to negatively affect the illusion.

RELATED WORK

The concept of *Substitutional Reality* implies the modification of the normally perceived reality through artificial means. Suzuki et al. [24], defined a *Substitutional Reality System* that, through a headset, was capable of manipulating users' perception of reality. It alternated a live video feed with previously recorded scenes so that users did not perceive any discontinuity. A related concept, *Virtualized Reality* [10] focused on the process of reconstructing virtual versions of real scenes. This way, users could experience real events from potentially unlimited viewpoints without any degradation in terms of visual and auditive realism during the reconstruction process. In the next section we define our vision of Substitutional Reality in the context of Virtual Reality. In the remainder of this section, we describe other research that shares common themes to those we investigated.

Passive Haptics — Previous work has shown that passive haptics can enhance the sense of presence. In a study by Hoffman [7], participants were immersed in a virtual kitchen environment and divided into two groups. In one, the interactive objects in the environment were purely virtual. In the other, the virtual objects were mapped to physical counterparts. Results showed that participants in the physical objects group guessed the object properties more accurately than those in the group subjected to the purely virtual condition. In a study by Insko et al. [8], participants had to place a book on a chair at the opposite end of a pit room by navigating on a ledge that separated them from the fall below. In one condition this ledge was substituted with a real wooden plank whereas in the other, the ledge was only virtual. Results showed that behavioural presence, heart rate, and skin conductivity changes had significant differences in the passive haptics condition. Indeed, participants could feel a height difference between the ledge they stood on and the floor below, enhancing the illusion of standing on the edge of a pit.

Passive haptics have also been used in studies using VR for medical purposes. In a study by Carlin et al. [2], a patient gradually interacted with a virtual spider to counteract her fear. A physical spider toy replica was mapped into the environment so that when the patient's virtual hand reached to touch the virtual spider, she could sense the furry texture of the toy. A Virtual Human paired to a mannequin was used by a system enabling inter-personal touch between a trainee physician and the agent posing as a breast-exam patient [13]. The results show that the use of passive haptics in the form of the mannequin and a physical breast simulator engaged participants to behave similar to human-human interaction.

Desktop VR — Nowadays, end-users can experience VR through headsets and conventional input devices. Past research on semi-immersive setups based on desktop displays has shown advantages in terms of better performance in a visual search task [21] in those scenarios not necessitating full immersion (e.g., browsing a scientific dataset). A drawback of this class of systems is the inability of using locomotion interfaces to move in the VE, which is considered to be beneficial to the sense of presence [26]. However, desktop SR could represent a first stepping stone as there are many scenarios in which substituting the user's immediate surroundings would suffice (e.g., racing or flight simulators). Augmented Reality (AR) [19] instead studies the real-time integration of virtual objects into the physical environment. Conversely, SR focuses on the integration of physical elements into a VE.

Visuo-Haptic Feedback — The biggest drawback of passive haptics is that any virtual alteration must also be reflected on the physical proxy, if visual fidelity is to be maintained. This can prove to be impractical. Haptic devices on the other hand, provide a more dynamic tactile experience. Works in the domain of Visuo-Haptic feedback have explored the use of these devices in conjunction with AR systems [3, 11]. In these works, users interact with a Phantom haptic device which is subsequently removed from the augmented video feed and substituted with a virtual object. For example in Knoerlein et al. [11], users play an AR version of ping-pong through the haptic device while seeing a virtual racket. Similarly, in Cosco et al. [3] users perform various tool-based tasks while interacting with a Phantom haptic device, replaced with a virtual tool. The benefits in terms of the haptic sensations come with the drawback of tying the user to the device. This negates the benefits of walking locomotion interfaces (unless the device can move with the user) and could be difficult to implement in domestic environments.

Robotic Manipulation — McNeely presented a robot that, when the user is about to touch a virtual object, places a physical object in their reach [17]. Tachi et al. [25], presented a *Shape Approximation Device*, a robot whose effector is capable of simulating contact with a variety of surfaces such as those having vertices, edges, and concave or convex parts.

Space Warping — The mapping between real and virtual objects has traditionally focused on a 1:1 match. In a study by Kohli et al. [12], the authors build on the concept that the sense of vision can take precedence over other senses in case of a conflict. They developed a technique called *Redirected Touching* which alters the way the user's virtual hand moves in the VE compared to its real movement.

Sensory Mismatch — Hinckley et al. [6] pioneered in a 1994 paper the use of a real object associated to a similar but not identical virtual object where a doll head model was used to control a brain visualization. The mismatch between visual feedback and other senses has also been investigated in studies on neurology and perception [1, 16]. In the context of AR, Kwon et al. [15] studied the extent to which mismatches in terms of shape and size affect user performance. They found better results when size and shape matched but no significant differences when size alone was altered. Steinicke et al. [23] presented a taxonomy of redirected walking techniques supporting ubiquitous passive haptic feedback. In the VR literature on locomotion interfaces, *redirected walking* refers to a range of techniques that are used to allow walking in VEs larger than the physical environment where the simulation is taking place. In the context of their work, redirected walking techniques are used to bring the user to a proxy object when they reach a similar object in the VE.

These works approach the problem of providing tactile feedback in a VE by building a physical environment that matches it as closely as possible or vice versa, the VE is designed as a copy of the physical environment. We approach the problem from a different angle. We focus on domestic environments where it is impractical to radically rearrange furniture or build matching props. Thus, instead of studying 1:1 physical/virtual pairings, our research assumes the existence of a mismatch and studies the extent to which it can be pushed.

SUBSTITUTIONAL REALITY

The Virtual Reality continuum introduced by Milgram [18] defines a range of possible "realities" altering our senses in different ways. At one end is the *Real Environment*, i.e. our normal experience of the world in which we live. At the other end is *Virtual Reality* where, in theory, every sense can be artificially stimulated. In between is the notion of Mixed Reality (MR), encompassing Augmented Reality and Augmented Virtuality [19]. These types of systems are usually characterised by adding or subtracting elements of either side of the continuum to the user experience.

Milgram defined a class of MR environments where *"real physical objects in the user's environment play a role in (or interfere with) the computer generated scene"* [18]. This class was named "Hybrid Reality". Since then, this term has been used in different contexts from location-based games [4] to large-scale data visualization [20].

VR systems and devices are now able to create highly visually and aurally convincing experiences. Current technology however, is still not able to stimulate our other senses with the same resolution. In particular, even though some technologies provide the experience of tactile feedback (e.g., haptic devices) and locomotion (e.g., omni-directional treadmills), these devices still are not able to mimic how we experience the real world. For example, haptic devices only stimulate the parts of the body where they touch, and are therefore unable to affect the body as a whole. Similarly, while treadmills allow users to navigate endlessly large spaces, they are unable to render physical obstacles or other terrain properties, such as ridges and uneven elevations.

To address the difficulty in rendering convincing physical and haptic experiences in VEs, we explore the concept of *Substitutional Reality* in the context of VR. That is, a class of MR environments in which a substitution process adapts a VE to the physical world. By substituting each physical element with a virtual counterpart, a VE is able to leverage physical properties to create convincing bodily experiences. We define the VE in which a substitution process has matched each virtual element with a physical element with varying degrees of mismatch, a *Substitutional Environment* (SE). If taken to extreme this would entail VEs that replicate the physical world. If any creative freedom is to be allowed, an SR system must be able to alter the elements in the virtual world to match the desired theme and feel of the SR experience.

To assist the design of how these elements can be altered, we provide a layered model of modification in which at each level the virtual element gets further away from its physical counterpart. Although we use the term *object*, this model applies to both small manipulable objects and large architectural features (e.g., walls, floors). To illustrate its structure, we use the example of a mug that exists in the real world, but is substituted in the VE with increasing levels of mismatch.

Replica — The basis of our model is constituted by substituted objects that are 1:1 replicas of their physical proxy. In a VE, the object will appear as a 3D model of the real one. It will present the same affordances and allow exactly the same interaction as its physical counterpart. In our example, the mug would be rendered as-is in the VE, matching every single one of its characteristics, from the material to little imperfections on its surface. Substitution at this level is the most realistic, but higher-fidelity systems would require either real-time reconstruction or pre-built models of existing objects.

Aesthetic — At this level, virtual and physical objects begin to differ, albeit from an aesthetic perspective. Physical properties regarding the appearance of a virtual object are altered without affecting the way the object is perceived. For example, in the VE the *material* of the mug might appear to be made out of glass or wood. This in turn affects the way an object can be perceived in terms of *temperature* and *weight*. If the mug is rendered as one carved out of ice, users might expect it to be colder to the touch and weigh differently.

Addition/Subtraction — Here, elements of either reality do not have counterparts in the other. Addition happens when parts of an object are rendered where there is no physical counterpart and subtraction happens when parts of a physical object do not have a virtual representation. Physical properties can be altered to varying degrees. For example, the *size* of the mug can be altered to portray a bigger or smaller version, or the mug might appear to lack a handle or have two on either side where the physical proxy only has one. Whereas this allows the design of richer environments (e.g., a room can be rendered as the captain's cabin in a pirate ship), this creates the risk of accidentally bumping into physical objects (e.g., in the said ship, going for a swim in the sea visible from the windows would result in bumping your head on the wall) and attempting to grasp non-existent parts of objects (reaching for the handle of a virtual glass, whose physical proxy lacks one).

Function — The alteration reaches the functional level when there is a mismatch between the affordances of physical and virtual elements. The concept of "affordance" introduced by Gibson [5] refers to the interaction possibilities perceived by the observer of an object. For instance, a mug *affords* drinking and pouring. In SR there could be a mismatch between the affordances portrayed by a substitutive object and those related to the physical proxy. However, users will interact with an object based on the affordances perceived by its virtual appearance. When some of these affordances are not shared, a functional mismatch appears. For example, the mug might be rendered as an oil lamp as they share some affordances (we can pour liquids in both) but are intended for two different functions (drinking or lighting). A mug and a similarly sized virtual box would have a greater functional mismatch: we can no longer pour liquids in both while the virtual box might have a lid. Affordances suggested by the virtual object but not present in the real object have a greater potential of negatively affecting the suspension of disbelief.

Category — Here, the substitution reaches the highest extreme. The virtual appearance of the object no longer has any connection to its physical counterpart. For example, if its *shape* is altered, a mug might be substituted by a box or a spherical ball. If we imagine these two objects to be sized within the bounding box of the original mug, parts of the space it occupies will appear to be empty (sphere) or filled (box). In addition, they no longer will share common affordances. As the virtual object distances itself from its proxy, the set of possible objects it can be substituted with increases and so does the likelihood of running into issues concerning the believability of the substitution and its ease of interaction. It is worth noting that the alteration does not have to be gradual, as the modification of specific physical properties can be enough to sever any recognizable connection the virtual object had with the original proxy.

We designed two studies that investigated the impact of the alterations defined in this model from two opposing perspectives. In the first study, we hypothesised that each substitution type would affect the believability of the experience to different degrees. To test this assumption and evaluate the extent of their effect, we presented participants with a physical object, a mug. However, in each trial of the study, the mug was matched to a different virtual object that exemplified a substitution type from the model. In the second study, we assumed that SR systems would frequently involve users in scenarios in which they need to interact with objects they might not possess (such as dangerous or imaginary objects, with the exception of props). Thus, we evaluated participants' engagement while wielding a Lightsaber replica and while wielding two substitutive objects: a torch and an umbrella. However, in the SE they were all perceived as the same Lightsaber.

APPARATUS

Here, we describe the physical room in which the two studies took place, the corresponding virtual room experienced by participants while immersed, and the equipment they used.

The Physical Room — Participants of our studies were tracked through a combination of 9 OptiTrack Flex 3 cameras. All cameras were placed at a height of $2.5\ m$. Four of these were placed at the corners. A fifth one was placed in the middle of the wall facing the entrance. The remaining four cameras were placed in the middle of the side walls, each oriented towards one half of the room's volume. Participants interacted with the environment in areas with optimal tracking coverage. In the first study they were sitting on a (real) sofa / (virtual) bench and did not incur tracking issues. In the second study, participants were instructed about the extents of the zone in which they could move while still being tracked, an area of $3\ m \times 2.75\ m$. We furnished our study room with furniture commonly found in a living room (see Figure 1): a desk with chair, a sofa, a cabinet, and a television plus stand. We measured the room's extents ($5.9\ m \times 3\ m$) and each object's bounding box. These measures were used to model the virtual objects substituting their real counterparts.

The Virtual Room — We designed two VEs using the Unity 4.5 engine. We built custom scripts in order to use VRPN data streamed by Motive, the software controlling the OptiTrack cameras. The data packets contained information on the absolute position and orientation of all tracked objects.

The User — Participants wore an *Oculus Rift* Development Kit 1 headset, working wirelessly through an HDMI receiver and an external battery inside a backpack. Absolute positioning and orientation data was provided by an optical marker attached to the Oculus Rift through a custom 3D printed mount. We mapped tracking data received from this marker to a stereoscopic camera representing the user's head in the VE. Participants also wore two fingerless gloves with optical markers attached on top. The markers were mapped to the position and orientation of two virtual forearm plus hand models that the user saw in the VE. We told participants that the movements of their fingers would not affect the pose of their virtual representation.

FIRST USER STUDY

In the first study, participants were immersed in an SE where our mock living room had been substituted by a medieval courtyard. Our goal for this study was to investigate the impact on the suspension of disbelief and ease of interaction that artificially increasing the mismatch between the virtual object and its physical counterpart could have. A baseline object, a replica of the real mug was recreated in the VE with the exact same size, shape, and visual appearance. The real mug measured $7\ m \times 10\ m \times 8\ cm$ and weighed $290\ g$. We considered various substituted objects, each altering a physical property exemplifying one of the substitution levels we previously described (see Figure 2). The substituted objects were:

Aesthetic — We altered the *material* of the mug, resulting in one appearing to be made out of *glass* and another appearing to be made out of *wood*; in addition, we also wanted to test the effect of materials suggesting explicit differences in terms of temperature, thus we designed a *hot* mug that appeared to be on fire and an *icy* one that appeared to be carved out of ice with a particle effect showing the ice sublimating.

Addition/Subtraction — We altered the *size* of the baseline mug with a *smaller* one (50% of the size) and a *bigger* one (150% of the size).

Function — We tested a *combination* of factors, i.e. different material, size, and addition and removal of features. The two resulting objects were a wooden basket of similar shape and size to the mug, save for the absence of the handles on the side and a lighted oil lamp in which one handle was approximated by the real handle of the mug (while the second was absent from the physical proxy).

Category — We wanted to test the effect a severely different *shape* had, thus we considered two substitutive objects: a box having the same bounding box of the mug and a sphere inscribed in said bounding box.

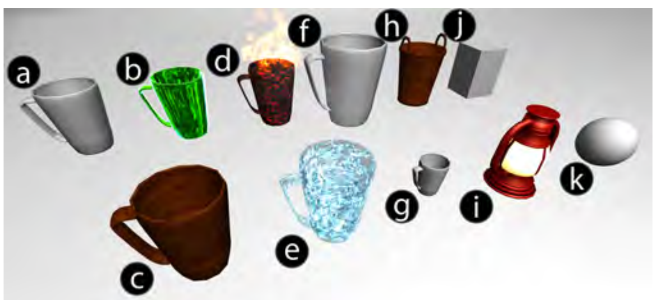

Figure 2. In the picture each pair of objects exemplifying a different substitution type is shown. The *replica* mug used as baseline *(a)* then each pair of substitutive objects: (*Aesthetic*) glass *(b)* and wooden mug *(c)*; hot *(d)* and icy mug *(e)*; (*Addition/Subtraction*) big *(f)* and small mug *(g)*; (*Function*) basket *(h)* and lamp *(i)*; (*Category*) box *(j)* and sphere *(k)*.

Since the impact of this mismatch was not known beforehand, we designed the virtual objects substituting furniture and other decorative elements that were not part of the main focus of the study by following a principle of plausibility. We chose the substitutive objects among those we believed participants would find plausible to find in such an outdoor environment. As it can be observed from Figure 1, wooden fences delimited the room on its two sides, while a stone arch with metal gate was placed in lieu of the real door leading into the room; the entrance to another house delimited the other end. The real-world desk from which the investigator controlled the experiment was substituted with a set of crates arranged in the same L-shape and size of its physical counterpart. The TV stand was substituted by a wooden beam to which a set of swords were attached (whose bounding box corresponded to the TV screen). Participants were sitting on a wooden bench that was modelled to the exact same size and shape of the real-world sofa, save for the absence of cushions which were replaced by a thicker wooden frame. Ambient sounds of birds and the wind played in the background.

Since we required a surface for the purpose of this study, we moved the cabinet in front of the sofa so that the objects of study could be placed on top. In the SE, the cabinet was replaced by a barrel having the same bounding box. Two objects were placed on top: a wine bottle (identical to the one in the real world) and a mug (the physical proxy we successively altered in the study). The real objects are shown in Figure 3. We augmented both objects with optical trackers (placed on top). The appearance of the wine bottle did not change during the course of the study. Its purpose was to support more complex interactions (such as pouring wine into the mug).

Task

Before beginning the first study, the investigator explained to the participants the concept of SR and the main implications it had on their surroundings: every virtual object they saw would be paired by a physical proxy. We informed participants that once immersed within the VE they would be presented with a number of different objects they had to interact with. We explained that the virtual appearance of the mug would change in each session. We asked participants to grab and feel the object, attempt to manipulate and use it in conjunction with the wine bottle.

Participants

Twenty participants (11 male, 9 female) aged 20-43 ($M = 27.35, SD = 5.12$) took part in the first study. One additional participant left the study midway due to nausea and was thus excluded from the analysis. We asked them to rate their experience with computer games and VR, on a scale of 1 (rarely play games/use VR technologies) to 7 (very frequently play games/use VR technologies). Our sample constituted of average gamers ($M = 4.64, SD = 1.35$) with low experience with VR technologies ($M = 2.50, SD = 1.50$). Each participant received £8.

Procedure

Before starting they completed a demographics questionnaire. They then put on the Oculus Rift and the two tracked gloves. The investigator placed the two real objects on the cabinet/barrel. Participants were not aware of what the real object looked like before the study began. At the end of each session, it was moved and then placed back for the successive session. Each participant was allowed to freely manipulate the virtual object for one minute, after which, we asked the participant to answer a set of questions on the experience of interacting with the object. Five of these questions required participants to rate on a 7-point scale how similar the virtual object felt to the real one in terms of *physical* properties such as *size*, *shape* (regardless of the apparent size), *temperature*, *material*, and *weight*. A value of 1 meant that the virtual object was completely different from the physical one; a value of 7 meant that they were exactly the same.

Two additional questions asked participants to rate on a 7-point scale the *perceived* properties of the object. The first, asked them to rate the *ease* of grabbing and manipulating the object, where 1 meant that the interaction was *very hard* and 7 meant that it was *very easy*. The second question asked how likely they were to believe that they were actually manipulating the virtual object, considering the overall mismatch between the two objects. A value of 1 meant that they were *completely distracted* from the idea of actually manipulating the virtual object, while a value of 7 meant that they were *completely absorbed* in the idea of actually manipulating it.

The investigator posed these questions while the participants were still wearing the Oculus Rift but after they had placed the object back on the barrel. The objects were presented in a balanced order. After completing each session, we asked participants to fill an SUS questionnaire on the sense of presence in the VE [22].

Results

We collected for each participant 77 responses ($7\ questions \times 11\ objects$), for a total of 1540. We compared the mean scores for each object in each category using a repeated-measures one-way ANOVA (Greenhouse-Geisser corrected when necessary) and post-hoc pairwise comparisons (Bonferroni corrected). The questionnaire results are summarised in Table 1.

		Material (Physical)	Temp. (Physical)	Size (Physical)	Shape (Physical)	Weight (Physical)	Ease (Perceived)	Suspension of Disbelief (Perceived)
Replica	Mean	4.95	5.74	6.05	6.35	4.78	6.25	5.85
Mug	SD	2.01	1.69	1.05	0.88	1.22	0.91	1.18
Aesthetic	Glass	0.55	0.26	0.20	0.10	0.85	0.00	0.20
(Material)	Wood	†-2.01	-1.57	-0.29	-0.13	-0.83	-0.36	-1.57
Aesthetic	Hot	*-2.70	*-4.34	-0.05	0.05	0.00	-0.55	*-2.55
(Temp.)	Icy	*-2.20	*-3.58	0.10	0.05	-0.20	-0.20	†-1.85
Addition	Big *(Size)*	0.05	-0.29	*-4.60	-0.65	*-3.00	-0.78	-1.06
Subtraction	Small *(Size)*	0.15	-0.54	*-3.15	-0.75	0.17	*-2.14	*-2.90
Function	Lamp	-1.70	*-2.84	†-1.30	*-4.00	-0.17	-1.20	-1.38
(Combined)	Basket	*-2.45	*-2.14	-0.25	*-2.45	-0.61	-0.70	-1.27
Categorical	Sphere	-1.19	-1.33	*-1.81	*-4.53	-1.31	*-1.66	*-3.38
(Shape)	Box	-0.89	-0.99	-0.52	*-4.82	-1.48	-1.07	*-2.79

Table 1. The first two rows report the replica mug's mean and standard deviation for each property, respectively. The remaining rows report the differences in the mean score of the object to the baseline, with statistically significant differences marked with † ($p < 0.05$) and * ($p < 0.01$).

The inflexibility of passive haptics showed in the participants' scores regarding their perception of the objects' *materials*. We found significant differences for the *Basket* ($M = 2.5$, $SD = 1.73$), the *Wooden* ($M = 2.94$, $SD = 1.95$), *Icy* ($M = 2.75$, $SD = 1.65$), and *Hot* mugs ($M = 2.25$, $SD = 1.65$). As expected, we found significant differences in terms of *temperature* for the *Icy* ($M = 2.16$, $SD = 1.12$) and *Hot* mugs ($M = 1.4$, $SD = 1.1$). Interestingly, participants expected the two objects that appeared to be made out of wood to be warmer: the *Wooden* ($M = 4.16$, $SD = 1.72$) mug and the *Basket* ($M = 3.6$, $SD = 1.6$). *Weight* was not a property we could alter in the substitutive objects. We did ask participants how much they thought the virtual representation should weigh compared to the one they were holding. We found a significant difference for the *Small* mug ($M = 1.78$, $SD = 1.06$). The *Box* trended towards significance ($M = 3.29$, $SD = 1.36$, $p = 0.57$). Indeed, we found that unambiguously communicating the correct material was not trivial. Some participants thought that the box was made out of paper, others of a concrete-like material.

Regarding differences between the visual appearance of the substitutive object and the physical proxy in terms of *size*, participants found the *Big* ($M = 2.9$, $SD = 1.83$) and *Small* mugs ($M = 1.45$, $SD = 0.6$), the *Sphere* ($M = 4.24$, $SD = 1.52$), and the *Lamp* ($M = 4.75$, $SD = 1.62$) to significantly vary. On the perception of the object's *shape*, we found significant differences regarding the *Sphere* ($M = 1.82$, $SD = 1.38$), the *Box* ($M = 1.53$, $SD = 0.8$), the *Lamp* ($M = 2.35$, $SD = 1.23$) and the *Basket* ($M = 3.9$, $SD = 1.58$).

Overall, we found that the objects that participants thought detracted from their suspension of disbelief were those that had a different shape or temperature. We found significant differences for the box ($M = 2.91$, $SD = 2.19$), the sphere ($M = 2.5$, $SD = 1.24$), the *Hot* mug ($M = 3.81$, $SD = 2.32$), and the *Icy* mug ($M = 4.21$, $SD = 2.04$). The *Small* mug ($M = 2.86$, $SD = 1.75$) was found to be less believable, while the bigger one was not. No significant differences from the believability of the baseline object were found for both the *Basket* ($M = 4.69$, $SD = 1.49$) and the *Lamp* ($M = 4.5$, $SD = 1.51$). Concerning the *ease* of interaction, only the *Small* mug ($M = 4.43$, $SD = 1.79$) and the *Sphere* ($M = 4.75$, $SD = 1.14$) were found to affect participants during manipulation, highlighting the issue *addition/subtraction* substitutions were likely to lead to. Finally, the mean SUS score, the sum of 6 or 7 ratings for each participant, was 2.5 ($SD = 1.79$).

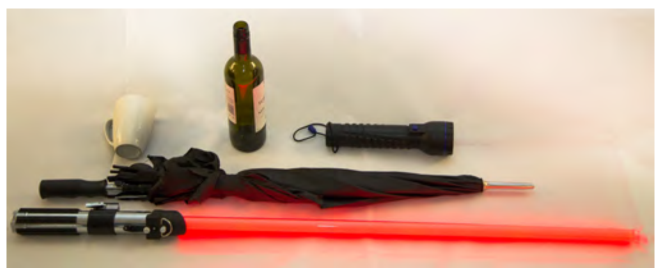

Figure 3. From left to right, top to bottom: the real mug and wine bottle used as physical props in the first study; the torch, umbrella, and Force FX replica of Darth Vader's Lightsaber used in the second study.

SECOND USER STUDY

In the second user study, participants were immersed in an SE where our mock living room had been turned into the bridge of a futuristic spaceship. Furniture was replaced by futuristic equivalents. An ambient sound of the engine humming played in the background. Our goal for this study was to investigate whether objects whose function differs from the one portrayed in the VE can be used to provide similar levels of engagement and support the suspension of disbelief as well as exact replicas. Often games present players with scenarios where they need to interact with various objects, such as guns, wizards' staves, swords, etc. In the context of SR it will be necessary to design experiences around the fact that these objects (especially the imaginary ones) are very unlikely to be found in users' living rooms. Thus, in most cases, the need to find a substitutive object becomes a necessity.

We designed a scenario in which participants needed to hit a moving target with a virtual Lightsaber matched to a physical proxy. We chose a replica as a baseline and two objects representative of substitution at the functional level. We did not consider categorical substitution as in the first study we found it to impact negatively the suspension of disbelief. Likewise, in a real world scenario we could not assume that users would possess examples of addition/subtraction or aesthetic substitution, e.g., Lightsabers of different sizes/colours. Our baseline object was a Force FX 1:1 replica of Darth Vader's Lightsaber from Star Wars ®. It consisted of a metal hilt and light tube, measuring 114 $cm \times 10\ cm \times 8\ cm$ and weighing 725 g. The other two objects were common household items: an umbrella (measuring 94 $cm \times 4\ cm \times 4\ cm$, weighing 520 g) and a torch (measuring 26 $cm \times 5\ cm \times 5\ cm$, weighing 214 g). These objects, shown in Figure 3, were chosen because they can be manipulated similar to the Lightsaber. However, they differ in shape, size, and perceived function.

Task

We asked participants to hit a moving blue sphere with their virtual Lightsaber. Each physical proxy had an optical tracker attached to it so that the movements and orientation of the virtual Lightsaber corresponded to those of the physical objects. We instructed them to stand in a specific spot in the room and explained that they could move, however the target was always in reach of the Lightsaber. The target moved across a pattern consisting of 9 positions arranged in a 3×3 grid centred at a distance of 1 m in front of the participant's starting position. The sphere stayed in a position for two seconds before moving to another randomly chosen grid-position (excluding the current one); the movement took one second. Once hit, the sphere turned green and a Lightsaber sound was played; it stayed green for one second before turning back blue. We instructed participants that hits performed while the sphere was green did not count. After hitting the sphere a total of nine times, the trial stopped.

Participants and Procedure

The same 20 participants who took part to the first study also took part to the second one. Each trial started after a countdown of three seconds. Participants repeated each session four times, the first of which was considered as training and was thus excluded from the analysis. They completed 3 *objects* $\times$ 3 *repetitions* for a total of 9 trials. Participants did not see any of the objects before the completion of the study. One of the investigators handed participants the objects when they were already wearing the headset. After completing each object's three trials, we asked participants to rate from 1 to 7 the following questions: how much they felt *engaged* or distracted in the idea of being a Jedi on a spaceship; their degree of *preference* for each object; how physically and mentally *exerted* they felt. In addition, we asked participants to guess which object they were really holding. Finally, we asked them to fill an SUS questionnaire.

Results

Results from the second study are summarised in Table 2. We measured average completion times: the *torch* was the fastest, followed by the *Lightsaber* and the umbrella; however, we did not find any significant differences. In terms of *engagement*, we found a significant effect for the object being used ($F_{2,57} = 294.83$, $p < 0.01$). When asked which object participants considered more supportive to the idea of actually wielding a Lightsaber, they gave the torch the highest rating, followed by the replica and then the umbrella. Pairwise comparison found a significant difference between the torch and the umbrella ($p < 0.01$).

We found a significant difference in terms of *preference* ($F_{2,57} = 287.68$, $p < 0.01$), with the torch being preferred to the umbrella ($p < 0.01$). When we asked to clarify the motivations for their preference, all participants stated that the weight was the main reason. Indeed we found a significant difference in terms of *physical exertion* ($F_{2,57} = 106.11$, $p < 0.02$), with the torch being reported as less tiring than both the replica and the umbrella ($p < 0.01$). This was further highlighted by their mean scores. No differences were found in terms of mental exertion. We asked participants to guess which object they were holding: out of 60 possible answers, 17 guessed correctly (28.33%). The mean SUS score, the sum of 6 or 7 ratings for each participant, was 2.5 ($SD = 1.91$).

Object	Time (s)	Engagement	Preference	Physical Ex.	Mental Ex.
Lightsaber	25.72 *(7.83)*	5.40 *(1.75)*	5.15 *(1.31)*	4.00 *(1.41)*	3.30 *(1.87)*
Umbrella	24.07 *(5.19)*	4.50 *(1.43)*	4.65 *(1.63)*	3.95 *(1.79)*	3.45 *(1.79)*
Torch	22.66 *(4.13)*	5.95 *(1.00)*	6.00 *(1.08)*	2.55 *(1.96)*	3.45 *(1.99)*
	Quantitative	*Qualitative*			

Table 2. Mean quantitative and qualitative results; in parentheses, the standard deviation.

DISCUSSION

We categorised our findings from the two studies in four main areas: design implications, content authoring, a discussion of open challenges, and of other application areas.

Design Implications

SR systems should prefer functional substitution for manipulable objects.

Overall, our results show that the choice of which substitutive object to assign to a real one is largely affected by the shape. However, if the extent of the substitution is maintained at the **functional** level, we found that there is a large leeway in terms of how much this can be altered. For instance, participants commented that the lamp object was regarded as being believable, however what broke the illusion was the missing handle (on one side, the mug handle approximated the lamp's). In the second study, more participants preferred the torch rather than the actual replica. The torch approximated only the hilt of the Lightsaber. Although it is unknown whether in reality the energy blade would have a significant weight, we believe the torch's lesser weight made it easier to manipulate than the replica (whose hilt was made out of metal) and the umbrella (also heavier).

Minimise mismatch with the manipulable parts of an object.

In order to minimise the impact that any mismatch has on the suspension of disbelief, we believe designers of SR systems should place greater emphasis in making substitutive objects closer to the proxy's physical appearance in the parts users are most likely to contact. For example, a pen would thus be a good candidate for a magic wand. The way a user would hold it is similar and the virtual magic wand can have a different shape at the opposite end from the hilt, as the user will be less likely to interact with it from that side.

Maintain correct proprioceptive feedback even if it conflicts with the real pose.
Regarding the **addition** or **subtraction** of features, smaller objects had a significant negative impact on the believability of the objects. This is largely due to the higher difficulty experienced by users in finding the physical object. Participants commented that it was harder to guess where the physical object was. They unexpectedly hit the real object while they saw their hand still distant from the virtual object. Objects that appeared bigger than they really were, did not cause a significant impact on the believability of the interaction. However, they reported some issues when their own hands could go through the bigger object's mesh. As we previously stated, we attached a single marker to the user's palm. With more sophisticated tracking systems it could be possible to track all fingers and use inverse kinematics to alter the pose of the fingers. For example, have the fingers appear to correctly grab a bigger looking object even though in reality, the fingers would be inside the object's mesh.

Out-of-reach objects allow for greater categorical mismatch.
We believe **categorical** substitution to be more suited for those objects that are least likely to be interacted with by the user, e.g., decorative or out-of-reach objects. If, however, there are no more suitable substitution options, we found that even though the extents of the mismatch broke the believability of the illusion, participants had few issues in actually being able to manipulate the objects.

Materials can affect users' expectation on the physical properties of the object.
Graphical realism, or substitution of **aesthetic** features is another key aspect that designers should keep in mind while creating SR experiences. We observed that participants experienced difficulties in understanding what objects were made of. This, in turn, caused users to perceive objects differently and thus generate assumptions based on the idea they had of the material. For example, 4 participants had conflicting opinions about the *box* object. For some, it appeared to be made out of paper, others of stone or concrete. One participant commented that *"The environment influenced my perception of the materials; as this looks like a medieval courtyard, I would not expect to find plastic here"*. As highlighted by our results, the ambient temperature of a material also needs to be taken into consideration as it was shown to have a significant impact on the believability of the illusion. In this regard, one participant commented while interacting with the hot mug, that *"if I had been wearing gloves, I would have believed it"*, similar to how oven mittens shield us from high temperatures.

The relation between an object's visual appearance and the physical properties it suggests can be manipulated by designers. They can alter the visual appearance of a material to influence users' expectations. For example, if a user is holding a virtual box, it could appear to be made out of iron if heavy or tin if light. In this way the user's suspension of disbelief will be improved by not perceiving a mismatch in terms of weight, even though there might be mismatches on other physical properties, e.g., the physical object might be made of a different material, such as plastic or have a different shape.

Substitutive objects can engage users as much as replicas.
Another observation we made, based on the results and the interviews with our participants, is that using objects that approximate the portrayed virtual object might be a better strategy than pursuing realistic physical-virtual object pairings. Even assuming that it could be practical to build high-fidelity replicas of objects needed in an SR system, even for dangerous or imaginary objects, using them might not be *fun*. Indeed, one of the main comments made by participants was that the Lightsaber replica and the umbrella were too heavy. This was also highlighted by the participants finding the torch to require less physical exertion. A convincing illusion of holding a machine gun or a longsword might constitute the goal of an "ultimate display". However, the real objects have considerable weights and require training to be used effectively. Thus, we believe this finding to generalise to other scenarios, that is: exact replicas are not necessary to maintain the suspension of disbelief; a substitutive object can be chosen among those able to provide a similar interactive experience to the one they portray; however it should not have undesirable qualities (e.g., being too heavy or fragile) even at the cost of increasing the mismatch with the actual object.

Reality-based VEs might have stricter presence requirements.
Although we did not find any significant differences in terms of the sense of presence in the two SEs, we collected some observations that highlight subjective differences between the two. One participant commented that *"I have really been in an environment similar to the [courtyard in the first study] so I know what to expect; I have never been on a spaceship and it seemed less real because I don't know what to compare it to"*. Another commented: *"Oh we are in Italy, aren't we?"*. We believe these and similar other comments to be an indicator of the first VE being more believable than the second as it was similar to places participants had really been to. This could implicate that it will be harder to maintain the suspension of disbelief while visiting VEs that look like common or really existing places. Users will form expectations based on their real experience of similar places that the VE needs to maintain in order to be perceived as believable. Conversely, designers will have more creative freedom when involving users in imaginary environments, as users will have less preconceived expectations.

Content Authoring

In our two studies we authored the SE manually. That is, we created a VE based on actual measurements. However, SR designers will have to design experiences that have to adapt to a wide variety of room environments. One key requirement is that future SR systems will need to have knowledge of the surrounding environment. This information ranges from data about the size and layout of the real environment in which a system is deployed (e.g., the user's house) to knowledge of the available objects' physical properties. The system will then enforce pairings between virtual objects and their physical counterparts, according to the requirements of the particular experience.

We envision two main avenues to recreate the user's own environment. On one end, an SR system could give users the means to create the basic layout of the environment, similar to *The Sims*' build mode. On the other end, it could be completely automatic. There are various mounts available to attach a depth camera to an Oculus Rift and it is conceivable that future headsets might have these sensors already built-in. Reconstruction systems such as the Kinect Fusion [9] allow users to capture the point cloud of any room. The advantage of SR is that it does not need a perfect approximation of the environment as its fundamental concept rests on non-perfect virtual-real pairings. Thus, we believe the tolerance of an environment resulting from a Kinect-Fusion capture would be acceptable for the purpose of extracting its basic layout features. Concerning the actual positional tracking of the user, the Oculus DK2 shipped with an add-on that is able to detect the user's head movements and orientation within 2.5 *m*. It is conceivable that off-the shelf tracking systems having greater range will become available in the near future.

Object recognition from 3D point-cloud datasets would then be the ideal method to detect which objects are available in a room and which substitutive objects would be the ideal candidates. However, manual labelling of objects the user wishes to be interactive in the SE would be the most cost-effective solution in the medium term. The SR system would then have to match the available objects with the substitutive objects needed in the game. This could be achieved by a rule-based system that privileged pairings that minimised the negative effects on the suspension of disbelief and ease of interaction. When no objects satisfying a rule are available, those having greater mismatch would be chosen. For example if an actual tablet cannot be found to substitute a futuristic one, then a book could be a good match as it could have similar size and affordances. The guidelines we presented in the previous section illustrate how such a system could favour these pairings.

Open Challenges

We believe that a similar investigation to the one we presented can be conducted to understand how the mismatch between larger physical objects and their virtual portrayal can impact real-walking locomotion interfaces.

In our studies, participants were not familiar with the objects used. In the first study, we observed that participants identified the object as a mug after manipulating it. In the second, the majority of users (71.67%) were not able to identify the object they held. Future research on SR systems deployed in real homes could investigate whether the user experience is affected by interacting with familiar objects.

Another challenge is represented by the disparity between the size of the VE and the space available in the real environment in which an SR experience takes place. A VR game can require very large spaces. For example, consider Carla: she is playing an SR experience at home. The SR system is able to adapt the locations in the VE to the rooms available in her own home. When the experience requires her to transition to another area, it would then be necessary to implement such a mechanism while avoiding her to wander outside the real boundaries (e.g., if her front door is also mapped to a virtual door). A naive implementation could require her to turn 180° when she reaches the door leading to the outside, as in the work of Williams et al. [27]. Upon completing the turn, she would find herself in a new environment, where the layout of her home continues to delimit the space she is allowed to explore. For example, if she is outside in a modern city environment, the real walls could be substituted by cars parked on one side of the street and a building façade on the other. In other outdoor environments, trees or fences could delimit the space available as we have done in the first study.

The existence of disparities between the user and their virtual avatar constitutes another challenge. In a VR game, the user is the real protagonist. In traditional computer games, the user impersonates a different character. Frequently, the abilities and skills of the game character differ from the user's real ones. In VR, this is no longer possible and our virtual avatar would be limited to our abilities. However it might still be desirable to provide "superhuman" capabilities. If our character possesses extraordinary strength, then designers can use the expectations we form based on an object's material to corroborate the illusion. For example, a cushion could be substituted by a heavy boulder that children playing the role of a superhero could throw on enemies.

Other Application Scenarios

The concept we have presented is not restricted to the domain of games. We envision that it can also have applications in educational contexts. For example, a museum could allocate a room for an SE that portrayed how everyday life was back in a different historical period. In this scenario, visitors could be immersed in an SR system that substituted the real environment with a Roman villa. Physical props could be used to provide a more engaging hands-on experience. For example, learning how the Romans prepared food by interacting with virtual utensils matched to physical proxies. Other areas of interest include training and simulation: fire-fighters or paramedics can simulate rescue operations taking place in virtual replicas of physical environments that are altered to look like an emergency is taking place. Sports represent another scenario: rock-climbers could substitute artificial walls with a mountain-side; hikers could experience remote environments while actually walking inside their own homes.

CONCLUSION

In this paper we investigated the concept of Substitutional Reality — Virtual Environments where the physical world is substituted with virtual counterparts. In particular, we studied how the mismatch between the virtual and the physical objects affects the user experience. A greater mismatch can increase the range of environments that can substitute the physical environment, but can also become an obstacle to the interaction and to the believability of the experience. We investigated the factors affecting this mismatch in two user studies.

Participants found the more believable substitutive objects to be those that do not have significant variations in the part most likely to be interacted with (a handle). They reported the mismatch to become significant when the virtual appearance suggested variations in terms of tactile feedback, temperature, and weight not portrayed by the physical proxy. However, we showed that designers can use these notions to simulate superhuman abilities (by matching heavy-looking materials with light objects) and increase the extent of the mismatch in the parts of objects least likely to be interacted with (a sword blade). In those cases where the exact object required by the experience might not be available (imaginary ones, for example), participants found interacting with a similar object as engaging as interacting with an actual replica. We envision that users will be able to participate in Virtual Reality experiences that can adapt to any uncontrolled environment. To this end, we believe our research will support future designers of Substitutional Reality systems and experiences.

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