

# Substitutional Reality: Towards a Research Agenda

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## ABSTRACT

In our previous work on Substitutional Reality, we presented an exploration of a class of Virtual Environments where every physical object surrounding the user is associated with appropriate virtual counterparts. Differently from “passive haptics”, Substitutional Reality assumes the existence of a discrepancy in the association. This previous work explored how far this mismatch can be pushed and its impact on the believability of the experience.

In this paper we discuss three main research directions for Substitutional Reality. Firstly, the design space is largely unexplored as the initial investigation focused on the mismatch between real and virtual objects. Secondly, the development of systems enabling a dynamic substitution process represents a key challenge. Thirdly, we discuss the meta-design process of these experiences.

**Index Terms:** H.5.1 [Information Interfaces and Presentation]: Artificial, augmented and virtual realities.

## 1 INTRODUCTION

Substitutional Reality (SR) [12] builds on the concept of associating virtual objects to physical proxies surrounding the user. The resulting *substituted* Virtual Environment or Substitutional Environment (SE), would be based on the physical environment in which the user is, but would look radically different (see Fig. 1). What differentiates SR from previous work on *passive haptics* [5] in the Virtual Reality (VR) literature, is the existence of a mismatch in this pairing. In our previous work, we have studied the extents of this mismatch in two user studies. From the results, we derived a set of guidelines supporting future designers of SR systems.

In this paper, we propose an SR research agenda and discuss new future directions. Further research on Substitutional Reality needs to tackle three different challenges: firstly, investigate in greater detail the SR design space; secondly, develop prototype SR systems capable of generating an SE based on the physical environment in which it is deployed; thirdly, explore the SR meta-design process: how to convey and evaluate abstract representations of a Virtual Environment that can then be adapted by an SR system to the requirements of each physical environment.

Indeed, our first work represents an initial exploration of the SR design space. We defined a layered model of potential substitutions which allowed us to explore the factors affecting the believability of the experience. From a conceptual point of view, there are several aspects that would be complementary to our first exploration. Our experiment focused on the mismatch between physical objects and their virtual counterparts. As such, it did not involve the possibility of really walking in the SE. Indeed, one of the greatest challenges of VR comes from the disparity between the simulated environment and the physical space in which the experience takes place. If there is no correspondence, walking in reality would pose safety issues due to the risk of bumping into walls or furniture users might not be aware of. While immersed in SE, users would be aware that the virtual objects they see are matched to tangible objects. The

awareness of these virtual objects delimiting the space in which they can move represents a way to untether users from the limitations of desktop-style VR. We also discuss other aspects that warrant further investigation in SR: such as exploring in greater detail the dimensions introduced by the model, how to combine immaterial and substituted objects, and how to approach multi-user SEs where users themselves are also subjected to a process of substitution.

The second issue focuses on the technical challenges of SR. In our previous work, the environments in which the users were immersed were manually authored. However, a real-world application of Substitutional Reality would require a system capable of dynamically producing an SE based on the physical environment given as input. As there are no existing systems capable of performing this process, it is unclear what kind of issues might arise and their implications on interaction and locomotion. We believe that research on SR *systems* could progress in incremental steps by first focusing on attainable goals such as dynamic substitution of the user’s surroundings (i.e. *desktop* SR), and then proceeding to tackle larger environments such as rooms and beyond. Once prototype SR systems are introduced, research can progress on studying advanced issues such as the combination of SR with mid-air haptics rendering systems or enabling substitution of outdoor environments.

The last issue concerns the meta-design process of SR experiences. Content creators will have to design SR experiences without knowing precisely in which physical environment they will be experienced. They could be vastly different in terms of both layout and object availability. We discuss how to approach this problem and the issue of evaluating different instances of the same SR experience.

## 2 RELATED WORK

The term *Substitutional Reality* was originally introduced by Suzuki et al. [15]. However, they focused on studying the impact of the alternation of live and recorded scenes on unaware users who were wearing a Head-Mounted Display. In the context of Virtual Reality, *Substitutional Reality* refers to a class of Virtual Environments where every physical object surrounding the user has been paired to a virtual object, on the assumption that a mismatch exists between the two [12].

Other works have focused on augmenting users’ own domestic environments to provide more compelling experiences. For example, Illumiroom is a proof-of-concept system by Jones et al. [8]. The system envisions the use of projected imagery to augment gaming experiences played on a regular display. It calibrates itself on the layout of the room in which it is installed and projects peripheral imagery. In this way, it can change the appearance of a room or extend the field of view of a game. For example, the area around the display can be used to show the rest of the game’s environment or extend a grenade’s bounce outside the display and into the room.

RoomAlive [7] is another proof-of-concept system that uses projected imagery to create a gaming experience in the user’s own living room. By reconstructing the main layout of the room in which the system is deployed, the system is able to identify planar surfaces. It can then project virtual objects and characters that users can interact with in game scenarios. For example, in a *whack-a-mole* scenario, virtual “moles” are rendered on the room’s walls or floors. The user can interact with them by whacking and shooting.

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Figure 1: Two Substitutional Environments from our previous work [12] based on the same physical living room: a medieval courtyard (left) and the bridge of a spaceship (right).

GravitySpace [1] is a system that, by means of a pressure-sensitive floor (which also acts as a display), is able to recreate a Virtual Environment based on what is happening above the floor. Using image-recognition techniques, the system analyses the contact points of furniture and people. Furniture are detected through their pressure and are uniquely identified by a rotation-invariant marker. Users are detected by matching their shoe footprint to a database of registered shoes. In this way the system is able to support various applications such as interactive games.

### 3 PERCEPTION IN SUBSTITUTIONAL REALITY

The model described in our previous work [12] identified a set of potential substitution types. This previous work explored the impact of each type, resulting in the identification of high-level factors that affect the user experience. From this starting point, there are several possible research directions in which further research is needed:

**Model** — In order to gain a deeper understanding of the design space of SR, it would be necessary to pursue further research in this direction. Is the model exhaustive? Are there other types of substitutions? Furthermore, it is necessary to investigate each layer of the model in greater detail. For example, in aesthetic substitutions, which type of materials have the least impact on the suspension of disbelief? At which point does a mismatch in size become significant? Considering the mismatch between the affordances [4] portrayed by the virtual object and those related to its physical proxy, are there cases of mismatch that have more impact than others?

**Locomotion** — Physically walking in a Virtual Environment is one of the overarching goals of Substitutional Reality and Virtual Reality [16]. As previously described, substitution will also incur with larger objects and architectural elements. It will thus be necessary to study the impact of the different types of substitution described in the model when applied to an environment in which users can physically move. There are a number of potential issues, for example: how to allow users to move in a Virtual Environment much larger than the space allowed by the physical environment. Past work have studied *Redirected Walking* techniques as a solution to this problem. Variations of these techniques could be applied to SR as well, however this could lead to participants experiencing the same obstacle patterns across different Virtual Environments, and it is unclear if this will negatively affect the sense of presence.

**Combining immaterial and substituted objects** — In our previous work [12], we found that objects that users are least likely to interact with can be subjected to substitutions having a greater mismatch. Indeed, objects that are out of reach could not even be matched to any physical element at all. However, there might be some situations in which an SR experience requires the portrayal of an element that cannot be matched to a physical object, which the user might interact with. For example, a protective force field surrounding an object the user needs to obtain. How can the suspension of disbelief be maintained in these situations? If the aforementioned force field looks convincingly dangerous, from a graphical

perspective, would it suffice to discourage users to interact with it and thus avoid breaking the illusion?

**Substitution of people** — Current technology allows systems to detect the posture of an user relatively easy. Given this information, it becomes then possible to assign a virtual avatar to substitute a real person in a co-operative scenario. Past work on Collaborative Virtual Environments has mostly focused on distributed networked telepresence, whereas co-located multi-user Virtual Reality systems have received less attention [10]. Game-like scenarios would be a suitable context in which to explore the combination of Substitutional Reality and multi-user Virtual Reality. If we imagine a group of 2 or more friends playing an SR game or visiting an SR version of a museum exhibit, there are various challenges to overcome:

- *Acceptance* — In the two studies performed in [12] participants were asked whether they would prefer to participate in SR experiences alone or with friends; results were mixed, therefore it would be necessary to investigate which factors can affect users' view of multi-user SR experiences.
- *Safety* — Can SR experiences safely involve scenarios in which players compete against each other (i.e. a sword-fighting game)? While this issue might not be exclusive to multi-user scenarios (i.e. accidentally hitting objects or interacting with those who appear less fragile than they are in reality), it raises the question of how best to approach it in the context of SR.
- *The role of non-participants* — It is conceivable that people (or even pets) who are not participating in an SR experience might enter the physical environment in which the SR system is deployed. As such they might interact with the environment. Seeing an object in the VE moving on its own might negatively affect the sense of presence. Analogously, if they are not represented in the environment, they effectively become obstacles that need to be avoided.

**User Interfaces** — The role of user interfaces is a challenging issue that is also relevant to Virtual Reality systems. However, in addition to the challenges of designing 3DUIs for system-control tasks, there are also some specific issues that would arise in SR experiences. For example, how can users change the status of the environment? Considering the scenario of a chest substituting a physical box, there exists a functional mismatch between the two. In the VE, the chest might be portrayed to be open in a different fashion than the box, or it might not be possible to open it at all. This mismatch can be mitigated by designing UIs that fill these gaps. For example, the previously described problem can be mitigated by presenting users with an on-screen inventory UI depicting the (entirely virtual) contents of said chest. This however leads back to the problem of combining objects that do not have an associated physical proxy and those who do, in the same SE.

## 4 TECHNICAL CHALLENGES

The development of real-time Substitutional Reality systems is one of the main research directions to pursue. There are two main challenges: 1) the development of a system capable of performing the substitution process, i.e. dynamically adapting a VE based on a physical environment given as input; 2) improving the tracking of users and objects in domestic environments.

### 4.1 Substitutional Reality Systems

We envision several types of SR systems, whose complexity increases with the scale of the physical environment they attempt to substitute. These are:

- **Desktop SR** — In some scenarios it may be sufficient to simulate only the user’s immediate surroundings. For example, in a racing or flight simulator the user is not expected to leave the car interior or cockpit during the duration of the simulation. Such an SR system would need to focus only on matching the objects available on the desktop and those needed by the VE. Users would not be able to walk within the simulated environment.
- **Room-Sized SR** — Substitution of room-sized domestic environments would be the logical next step. The SR system would adapt the VE required by the experience to the space available in the physical environment. The system would need to track non-static manipulable objects.
- **Large-Scale SR** — Substituting any kind of environment in which an SR system is deployed could represent the ultimate goal. This would require new research on non-intrusive sensing devices. Investigating how to enable SR in outdoor environments could be another direction.

In the short to medium term, we believe *Desktop* and *Room-Sized* SR to be the most feasible and achievable goals, with *Large-Scale* SR driving the overall vision.

The prerequisite to the substitution process is the reconstruction of a 3D version of a physical environment. This has been shown to be possible even with commodity hardware. For example, Kinect Fusion [6] is a real time reconstruction system that, through a depth-camera, is able to create the point-cloud of the environment in which it is used. In some applications, it is necessary to reconstruct an environment with as much fidelity as possible, for example for Telepresence or Augmented Reality [3]. However, in the context of Substitutional Reality, a coarser representation might suffice. The goal of this substitution process would not be the building of a VE acting as a replica of the real environment the user is in, but the creation of one that uses its physical elements to provide tangibility to a radically different VE. We envision a substitution process consisting of several steps:

1. Retrieve the point cloud of the physical environment to substitute.
2. Detect the main features of the environment (e.g., the floor, walls, and ceiling, see Fig. 2).
3. Segment furniture and other objects.
4. Fit bounding boxes on each segmented object (see Fig. 3).
5. Detect semantic information.
6. Match physical objects with virtual objects required from the Substitutional Reality experience.

Our initial experimentations are based on the analysis of a static point cloud frame, using the Point Cloud Library [11]. After removing the planes constituting the floor, ceiling and walls, the remaining point cloud represents the objects in the room. A variety

of segmentation algorithms can be used to divide them into clusters (see Fig. 5). Once objects are separated into clusters (on a coarse scale), it would be possible to fit bounding boxes onto each.

Beyond the implementation of an SR system, a further goal would be the artificial simulation of the mismatch between physical and virtual objects. For example, projects like Aired [14] and Ultrahaptics [2] allow users to sense mid-air haptic feedback. Further research in that direction could investigate how to use a physical proxy and render its missing features, in order to enhance the believability of the illusion. For example, given a real torch as proxy for a Lightsaber, it is conceivable that the real object would lack some features of the virtual object, i.e. an example of “addition/subtraction” of features. Ideally, the haptic system would render the missing features of the Lightsaber, such as the activation switch, ridges in the hilt, etc.

### 4.2 User and Object tracking

An SR system will require technologies capable of sensing the user’s position by using devices that do not require a radical augmentation of the physical environment. A number of consumer full-body motion tracking devices are being developed with the intent of reducing the cost of this technology, for example STEM [13] and PrioVR [18].

Tracking objects users wish to interact with represents the other side of this challenge. Real-time object segmentation and classification might be the long-term goal. However, in the shorter term, individually tracking objects users explicitly wish to be interactive could represent a more cost-effective solution. Indeed, this method has the advantage of not needing to infer semantic information from its visual representation, as the user would label it manually. However, the disadvantage consists in the physical tangibility of the sensor itself which could negatively affect the sense of presence. In our previous work, we placed IR markers on objects that users were less likely to be interacted with, such as a mug’s top or a bottle’s neck.

## 5 DESIGN AND EVALUATION OF SR EXPERIENCES

Once proof-of-concept SR systems are available, investigating the meta-design process of SR experiences would be the next challenge to explore. An SR experience, be it game-oriented or educational in nature, should describe tasks or activities the participants can perform while immersed in the system. However, in conventional games the whole experience takes place in a simulated environment on which the designers have complete artistic control.

In SR, designers will not be aware of the environment in which an experience will take place. Therefore, its design process will need to convey the logic and progression of the experience in an abstract form that does not rely on absolute spatial information (i.e. a task might require users to find an object located on a shelf in the north-western corner of a room) but presents the information in a way that can be dynamically adapted by the system (i.e. users need to find an object located on a planar surface, near a window). In this regard, the design of SR experiences might build on the insights and methodologies of *Procedural Content Generation* [9]. Thus, investigating how best to represent this information and how to approach the SR design process will need further research.

Finding a method to obtain an objective measure of the mismatch between the physical environment and the portrayed Virtual Environment represents another challenge. This measure could be useful to compare the same SR experience across different physical environments (performing a study similar to the original work of Usoh et al. [17]). Studying its relationship with the sense of presence would provide more insights into which factors have the most impact on the believability of the experience. For example, is the mismatch between physical and virtual objects equally important as the mismatch between the physical location and the virtual counterpart (e.g., a real living room substituted by a different virtual room

of another building as opposed to a virtual outdoor location) or not? Is there a limit to the level of mismatch admissible over which an SR experience is no longer feasible in a given physical environment? Finding the answers to these questions will shed further insights on the design space of SR.

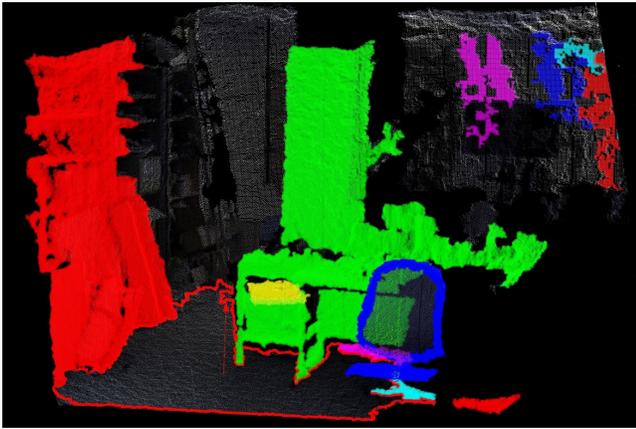


Figure 2: In the picture, an example output of the segmentation of planar surfaces and large object clusters is shown.

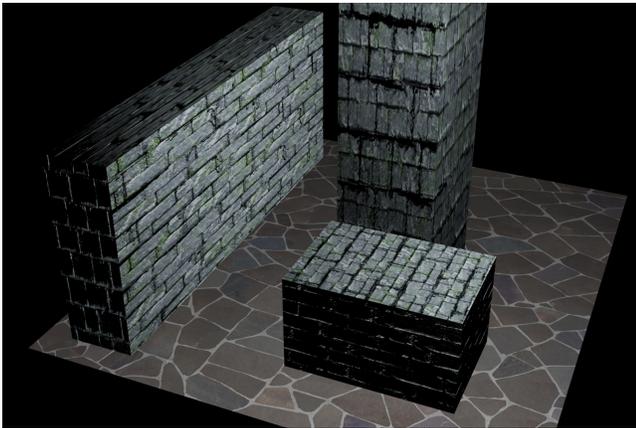


Figure 3: A concept representation of using the output of the previous step in the substitution process (see Fig. 5) to create a 3D environment based on the point cloud captured by a depth camera.

## 6 CONCLUSION

In this paper we have proposed a Substitutional Reality research agenda focusing on three main directions. The first is to pursue further research on aspects that are yet unexplored, such as a deeper characterisation of the model defined in our previous work; the challenges of locomotion in Substitutional Reality; the combination of immaterial and substituted objects; the possibility of substituting people in multi-user systems. The second direction explores the technical aspects of Substitutional Reality: from systems enabling dynamic adaptation of the Virtual Environment based on the layout of the input physical environment to the sensing technology needed to support them. The third direction focuses on the meta-design process of SR experiences.

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