Seamless, Bi-directional Transitions along the Reality-Virtuality Continuum: A Conceptualization and Prototype Exploration

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Abstract

With head mounted displays, consumers are able to transition from the real world to virtual realities. However, this requires frequent transitions between the two realities to maintain their physical integrity and awareness of the real world while in the virtual space. We completed two consecutive studies to investigate the dimensions of a system that supports seamless transition between realities without requiring the user to remove the headset. Our results are twofold: First, based on the the analysis of structured interviews (*n*=20), we present a conceptualization of existing solutions (*n*=37) and novel ideas (*n*=9) in the form of a design space. Second, we present the results of a user study (*n*=36) in which we tested two exemplary prototypes that evolved from the design space, called "Sky Portal" and "Virtual Phone." Our exploration shows that our "Virtual Phone" metaphor has the potential to support HMD users in completing bi-directional transitions along Milgram's reality-virtuality continuum. Users are also enabled to complete micro-interactions across the realities, even without performance loss.

Index Terms: Human-centered computing Mixed / augmented reality—;——

1 Introduction & Background

In a closed lab setting or private living room, immersive *head-mounted display* (HMD) users can manage physical integrity by defining the play area to avoid physical obstacles, and they can control who enters the room by locking it. However, moving outside of these controlled settings into a dynamically changing environment, such as an open office with co-located bystanders, demands an increased awareness of the real environment.

We want to amplify this thought by treating both environments equally, such that the user is aware of the real environment (RE) while in the virtual environment (VE) and vice versa. We envision users to do so without taking the headset off – which we refer to as seamless transition.

A user may, for example, take part in a prototyping session in VE with remote collaborators, while they are sitting in a shared, physical office space. In this scenario, they want to be aware of events in the real environment, such as a colleague approaching or a phone ringing, and be able to complete micro-interactions, such as looking up their notes in a book. We want to empower the user to seamlessly transition – rather than step out by taking the headset off – into RE to engage with the physical colleague/object, while still being aware/be part of of the prototyping progress in VE. Our aim is to support the user to be in both environments at once by treating these equally and enabling a seamless bi-directional transition. In the context of this paper bi-directional means that transitions are performed in the same way in both directions.

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A challenge in this context is one of the quality measures of VE, namely *presence*. This term refers to the subjective feeling of *being in VE* – frequently measured by how much the HMD user is not aware of the real environment [58, 71]. At first glance, this seems contradictory to the idea of being equally present in both environments; however, we propose to shift the paradigm from striving towards maximal presence, excluding the real environment, towards *optimal presence*, a balanced inclusion of the RE, to maintain physical integrity and privacy.

Riva et al. [53] first introduced this term to describe a state in which "biologically and culturally determined cognitive processes are working in harmony." This is in contrast to maximal presence, whereby users are immersed in a "story," losing touch of their own self in the external environment. Ijsselsteijn et al. [34] differentiate between these two terms by proposing that maximal presence is what the system is capable of achieving, whereas optimal presence is what the user needs in a specific context (e.g. not showing their home during a video call [6]).

Although neither of these authors mention the inclusion of the RE to achieve optimal presence, we argue that our proposal is in line with their discussion. Riva et al.'s discussion is framed around users' awareness of their self in the external environment whilst immersing themselves in VE. They explicitly do not differentiate between the real and virtual environment. We expand on this thought by suggesting that the management of physical integrity is vital in order to deepen awareness of the user's self in both environments.

Similarly, we are in agreement with Ijsselsteijn's definition that co-located places demand optimal presence rather than maximal presence, due to the variability in user (e.g. privacy) and context (e.g. open office vs lab) needs.

Of course, this paradigm shift means that the user is transitioning along a continuum rather than from one extreme to the other – VE to RE or vice versa. Milgram's reality-virtuality continuum [46] provides an insight into the transition states that the user can be in, from VE to augmented virtuality (AV), to augmented reality (AR), and finally to RE. Notably, Milgram discussed the possibility of additional in-between states which was investigated by Benford et al. [4]. We want to explore how transitions between Milgram's states can be supported in both directions. Due to the increased research interest in VEs in the last years, there exist a vast number of solutions that enable awareness of the RE. Although they all have a common aim, it is unclear whether they are striving towards optimal presence as we have defined it. Furthermore, there is a high variance in user needs, system requirements and the success measures they use. In light of these uncertainties, there is a need to analyze existing solutions and identify aspects that contribute towards concepts which allow HMD users to be in both environments at once without taking the headset off. We refer to these as seamless transition concepts (SeaT).

Our work is guided by the following research questions:

RQ1 What dimensions make up a design space for seamless transition concepts?

RQ2 How do users interact with a seamless bi-directional transition solution and what effects does such a solution have on factors such as, presence, performance and safety.

We completed two consecutive studies to investigate these research questions. Firstly, expert and novice interviews (n=20) to identify (i) factors that influence seamless transition concepts, (ii) established solutions in this context, and (iii) novel ideas that have not been addressed in prior work. From this analysis of 37 publications, we contribute a design space of seamless transition concepts.

Secondly, a user study (n=36), in which we tested two exemplary prototypes – sky portal and virtual phone – for transitioning between realities. Our solutions successfully support bi-directional transitions to perform micro-interactions. Contrary to prior work, interactions that enable transitions in our solutions are designed for both directions – VE to RE and RE to VE – in the same way, thus treating the environments equally.

2 Design Space for Seamless Transitions

To investigate our research question, we used a sequential mixed-method design. First, we conducted an interview with VE experts (n=10) – researchers and industry experts (e.g. developers) with more than 4+ years experience creating and designing VE experiences – and VE enthusiasts (n=10) – who regularly use VE for work and gaming but do not actively contribute towards it. Second, we completed a literature review on 37 publications to conceptualize the design space.

2.1 Method

Interviews were closely aligned with a storytelling task [13]. Our VE experts and enthusiasts were given the beginning of a story: "Alex was working in a shared office space while prototyping in VE with an HMD. He had co-located colleagues working in the real, physical environment, who regularly wanted to engage with him to discuss the prototype they were working on together. However, Alex did not want to take off his HMD, in order to maintain his presence in the VE." The participants were then required to complete the story, and talk about possible interactions between the characters and how technology may be involved. Subsequently, they were asked specific questions on how awareness of the real environment may be improved when immersed in VE and whether there are published solutions that would allow HMD users to transition between the environments. Interviews lasted approximately 10 min.

2.2 Analysis

Transcripts from the interviews were analyzed through thematic analysis [7] by two researchers. Themes were determined in an iterative process based on theoretical relevance: In the first round, authors separately read the transcripts and identified potential themes. Transcripts were re-read until no further themes were identified. The authors then combined their themes and mutually agreed on overarching themes by carefully considering the depth of the underlying sub-themes. Creating a design space out of the themes (**RQ1**) informed this analysis. Finally, the authors re-evaluated the naming of the themes to form a coherent design space.

2.3 Results

The thematic analysis of the storytelling exercise revealed four main themes with varying sub-themes and the follow up interview 46 solutions. From the latter, 37 were based on published work and nine are, to the best of our knowledge, novel ideas.

The storytelling method was chosen as it can capture the mental model of participants beyond what is currently available/possible. Thus, the choice of method resulted in the decision to include *all* solutions that were mentioned by our participants, even if the solution – in its current state – was not bi-directional or could not enable transitions. In the minds of the participants, the solutions had the *potential* for bi-directional transitions. This approach resulted in only a minority of mentioned solutions solely focusing on the concept of seamless transitions between environments. Instead, participants pointed out solutions that increased awareness of the other environment and also had the potential to be used as bi-directional transition concepts, either in their own right, or as a contribution towards one (e.g. [22, 24, 48]).

The aim of the design space is not to offer a comprehensive literature review but rather provide a conceptualization with exemplary [published] solutions. Some solutions appear multiple times in the design space, as one solution may support multiple dimensions. Our design space and the requirements analysis is available online and may be extended [18].

2.4 Design Space Dimensions

We consider the themes arising from the analysis of the interviews, along with solutions from past research, to build the dimensions of the design space. Our design space for seamless transition (SeaT) between environments consists of four dimensions, described below and summarized in table 1. The quotes mentioned in the following section are direct translations from the interviews.

2.4.1 D1: Motivation for Transition

We found solutions to address different motivations for transitioning between environments.

Social interaction & collaboration describes the HMD user's need to communicate and interact with bystanders. *"If it was a short interaction I would leave the headset off but otherwise I would take it off to communicate." (P7).* The importance of eye contact was also mentioned by multiple participants.

Solutions in this dimension support this by displaying the VE user's face to the bystander [42] but also by enabling two-way interactions [12, 25, 33, 36]. Kunert et al. [37] investigated varying perspectives and screens for collaborative 3D interaction. Prior work reviewed non-verbal interaction as a success factor for VE collaboration, such as gestures within VE [51] and unintentional gestures to bystanders [20].

Physical integrity & orientation summarizes the safety and self-orientation of users, independent of the environment they are currently in. One example is a VE user's need for physical integrity – not colliding with objects and bystanders. Awareness of their location within the real environment – in proximity to bystanders – while immersed in VE, supports physical integrity. Participants thought that this was vital and they manage it by *"locking the door" (P5)* or by trusting their colleagues to *"take care of them" (P4)* while they are in VR. In the absence of the latter management tactics, they would take the headset off. Previous work has provided solutions whereby the VE is overlayed with physical objects to support orientation and avoid injuries [25, 39].

Awareness of the other environment in order to maintain presence across environments independent of which one the user is mainly working on. For example, the HMD user may be working in VE, while also wanting to be aware of changes in the physical environment. *"If there was no one around to let me know what the noise in the real world was, such us the door opening, then I would take the headset off." (P9). "[...] not having to take off my headset every time I am worried about something in the real world, would save me a lot of time". (P16).* This is a common problem in other devices, such as mobile phones and desktop computers, which is why interruptions is a prominent research area in HCI. Similarly, interruptions [20] and more specifically, notifications [19, 23] have gained research interest in immersive HMDs. Of course, rendering parts of the physical environment into VE was seen to increase awareness of the other environment [29, 61]. To further assist with awareness, the concept of portals has already been discussed in prior work, in the form of physical portals [36], the form of a tangible curtain metaphor with

Table 1: Summary of seamless transition (SeaT) design space with three dimensions. The design space is the result of a qualitative study (N=20) which revealed 37 solutions from prior work and 9 novel ideas. Novel ideas are denoted with a (*).

D2: Availability	D3: Modality	D1: Motivation for Transitions: Social interaction & collaboration	Physical integrity & orientation	Awareness	Interaction with physical & virtual objects
continuous	visual	displaying the VE users face to the bystander [42], gestures within VE [51], microphone volume display to indicate importance of noise from RE (*)	virtual replica of a physical space [39] vs RE with virtual objects [25]	rendering parts of situated reality into VE [29, 61], mirror to peek into other world (*)	blending physical objects into VE that can be reused and edited [29, 61, 63]
continuous	audio	two-way Audio stream for communication between RE and VE [3, 47], make RE auditory signals prominent in VE depending on importance (*)	auditory border signals (*)	audio footsteps in VR to increase awareness of self (& others) [32], footsteps of non-HMD Users (*)	
continuous	haptic	interactive touchscreen for non HMD user [29, 40], toy spider and VE spider mapping [17]	haptic border signals (*)	elephant sensing [41]	including physical objects, such as sand [16] or water [50] as interface medium, blending and editing VEs with physical objects [29]
continuous	visual & audio	bi-directional audio stream [3, 22], greek god hand metaphor to interact with VR from VE and RE [31]	VE representation of physical object with sound [66]	traversable interfaces as portals between environments [36]	
system-triggered	visual	notifications [19, 23, 48, 57], blending bystanders upon proximity [44], image of physical bystander to VE user [12] and of HMD user to bystander [42]	virtual dynamic boundaries with physical objects [72], blending physical objects and people based on proximity [44, 69], physical border management with multiple VE users [43]	map of VE to increase awareness [47, 62], metaphors for receiving notifications (doorbell, push) [70]	physical bystanders interacting with VE [25, 26], portal on the ceiling (*, can only be displayed when users look up or continuously)
system-triggered	audio	notifications [23, 57]			
system-triggered	haptic	notifications [23, 57]			
user-triggered	visual	tangible book to support transitions between realities [5], partial passthrough vision to peek into *other* reality (*)		xRay vision to peek into *other* reality [30]	
user-triggered	audio			compass of objects/people in other world (*)	
user-triggered	haptic	tangible book for transitions [5], photoportals as transition concept to jump to a specific place/time [37]		metaphor for peeking into reality [70]	
user-triggered	visual &audio	holoportation for transitioning in real time [49]		VE representation of physical object with sound [66]	

a CAVE system, and as virtual windows to the physical environment [70]. Benford et al. [4] specifically investigate the transition between environments by augmenting physical spaces with video projections of virtual environments.

Interaction with physical and virtual objects independent of the environment in which the user is. For example, the HMD user may be working in VE but needs access to a physical object with written notes on it (e.g. notepad, low-fi prototype). Prior solutions investigated blending physical objects into VE that can be reused and edited [29, 61, 63]. Prior work also reviewed how specific physical objects and their differences in tangibility (sand vs. water) may be represented and augmented in VE [16, 50].

2.4.2 D2: Availability

When and how to change between environments varied between our participants. *"Changing the medium [VE vs. RE] is tiring. I would prefer staying in one, even if I had to quickly do something in the other." (P9).*

Solutions may be differentiated by their availability to the user: They can be user-triggered, system-triggered or continuous.

MagicBook is a user-triggered solution that enables users to transition between environment and virtuality by using a tangible book [5]. Photoportals [37] uses the concept of photos as a window to another virtual scene: Although they stay within one environment in this concept, images within other environments can be captured and used as portals.

System-triggered solutions mainly address interruptions research for VE, such as notifying the VE user of co-located users in the form of real-time renderings of bystanders [45] or by more abstract methods, such as spot-lights [19] in the VE scene. These solutions may be extended, such that the placement of the virtual object/person is equal to their location in the real environment. Communication requests [12, 23] may also be used as a portal to another environment. However, awareness of the real environment is also systematically triggered by displaying visual boundaries that stop HMD users from colliding with physical obstacles [72]. Similarly, there are solutions where extracts of the real environment are rendered into the virtual one, such as [30, 39, 44]. This may be extended by using the visual boundaries as borders that are used as transition points/portals into the other environment. Communication to non-HMD users is also

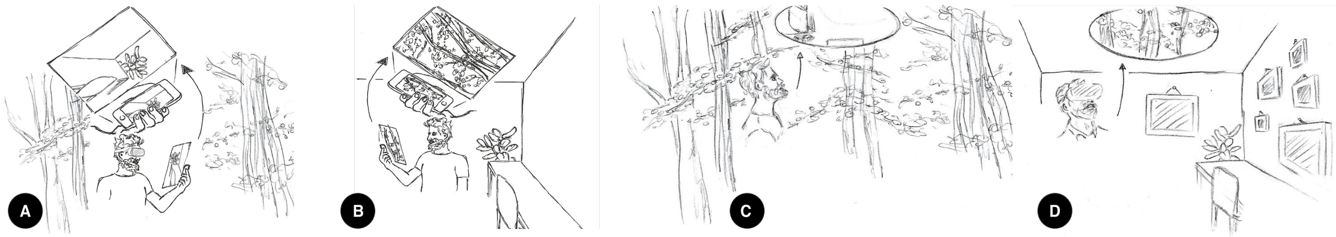

Figure 1: Early concept sketches of exemplary prototypes. On the left (A for VE view & B for RE view), the user-triggered virtual phone acts as tangible window to the other environment. "Tangible window" refers to a smartphone that acts as a window to the other reality. For example, when viewing the scene on a smartphone in the real environment, gestures such as pinching and zooming into a VE scene are possible. On the right (C for VE view & D for RE view), is the continuously available sky portal.

a prominent theme, such as a video call between virtual and real environment users [22, 52]. Although the majority of solutions focuses on increasing awareness of the real environment while in VE, there are also user- and system triggered solutions where the virtual environment is displayed to the real environment bystander [26, 42].

Continuous solutions are prominently mentioned in prior work in the context of collaborations, such as displaying real environment [non-HMD] bystanders [25, 49, 67], and within Tracs [38], where users are able to control which parts of their screen are visible to others. Similar concepts can be envisioned for VE, where HMD users can share parts of their virtual scene with real environment bystanders, with the shared part as the portal between the environments.

2.4.3 D3: Modality

The majority of participants spoke about solutions that were visual and involved blending aspects of one environment into the other. However, audio was also a prominent channel. *"A familiar voice tells me about things going on in the other world through my headphones" (P1).* Solutions may be differentiated based on the modality they focus on. The majority of existing once uses the visual modality, such as blending in bystanders in close proximity [45] and the display of boundaries [72] in VR. Audio and haptic are predominantly used as complementary features [33, 66]. Audio-only was discussed in prior work by George et al., who compared audio instructions with audio & visual instructions between bystanders and HMD users [22], and Ghosh et al. [23], in the context of interruptions. Mai et al. proposed a system that focused on the haptic modality by providing directional floor vibrations when bystanders are sensed [41].

2.4.4 D4: The Act of Transitioning

One expert participant pointed out that *"the act of transitioning itself" (P3)*, should also be taken into consideration. We did not include it in our summary in table 1, as there were no specific solutions from prior work mentioned by any of our participants. However, during our analysis we explored the idea to use in-between environments along Milgram's continuum [46] to ease the transition from one environment to the other. For example, instead of putting a VE headset on to experience VR and being placed immediately into the VE, the transition may be done in a gradual way, such that the user enters an augmented reality first. In this environment, (some) virtual objects from the VE can already be displayed, so that users can orientate themselves and the virtual objects in context of their RE. Gradually, the other virtual objects are included until only the VE is visible. Of course, this idea can be done in reverse as the user exits. Such a gradual transition may improve physical integrity and awareness, and our future work may explore the feasibility of such a solution.

2.5 Discussion

The SeaT-design space highlights the lack of a bi-directional, seamless transition solution that works equally in both directions. Specifically, it shows gaps in areas such as *physical integrity* and bi-directional *interaction with physical and virtual objects*, which require more attention. Similarly, *user-triggered* solutions have been less of a priority so far. Recent work has considered the importance of empowering users to choose the extent of virtual reality they want to experience. Slater et al. [64] discuss the importance of degrees of virtual reality that users can immerse themselves in, and George et al.'s field study confirms this while pointing out HMD users' need for privacy and safety [21].

2.5.1 Opportunity for Extending the SeaT Design Space

Our design space is based on interviews with VE experts and non-expert enthusiasts, with the aim to provide the current view of existing solutions and the factors that researchers and practitioners deem to be important. However, in order to explore further where there is a lack of solutions necessary for co-located collaborative interactions between HMD users and RE bystanders, the design space may be extended to include prior work in CSCW. There is, for example, the potential to expand the first dimension (D1); specifically social interaction & collaboration with prior work from Gutwin et al. [27]. Comparing our design space and the requirements with Gutwin's mechanics of collaboration, we can see that the majority of our solutions support *consequential communication* and *coordination* rather than, for example, *monitoring* (e.g. interpreting unintentional and intentional gestures) and protection (e.g. private vs shared virtual and physical spaces). Similarly, there is prior work in related areas with novel technologies that provides design guidelines for co-located collaboration (e.g. tabletop guidelines [60]). It is beyond the scope of this paper to do this type of analysis, however, from a methodological perspective, we perceive these two approaches to be complementary.

2.5.2 Considerations for Usage

Due to the nature of qualitative analysis, specifically our choice of method, we cannot exclude experimenter bias. Thus, there may be alternative structures to organize the dimensions of our design space, for example, exchanging the order of the dimensions *D2: availability* and *D3: modality*. However, we argue that the individual dimensions and sub-dimensions form prominent design guidelines, independent of the order of priority they are used in.

To summarize, through conceptualizing solutions in form of the SeaT-design space, we (i) reveal gaps that highlight a lack of research in certain dimensions, and (ii) provide novel ideas for seamless transition concepts. In the next sections, we apply our findings by developing two solutions from the design space and testing them in a user study.

3 Exemplary Prototype

To understand how users interact with a seamless bi-directional transition solution, we iteratively developed two exemplary prototypes (**RQ2**), based on the SeaT- design space. In the following section we describe the ideation, design and implementation of the prototypes.

3.1 Ideation & Design

As a first step, we decided to focus on the novel ideas in the SeaT design space – marked (*). These ideas can be grouped into visual vs haptic/audio solutions, whereby this paper focuses on visual ones. This approach results in four novel ideas, namely: (1) user-triggered "partial pass-through vision to peek into other reality," (2) continuous "mirror to peek into other world," (3) "portal on the ceiling" and "microphone volume display."

Next, we iteratively created low-fi sketches of possible prototypes, based on the above ideas. Considering the complexity of Milgram's continuum [46], our aim during these sketching rounds was to create interaction concepts that users were already familiar with, empowering them to transition existing knowledge (e.g. smartphone interaction) to a new domain – which in our case is the seamless transition between the environments. This aim motivated our usage of metaphors. The latter is a popular tool within HCI research. Jamar et al. [35] define it as "[...] tools we use to link highly technical, complex software with the user's everyday environment."

This iterative process resulted in the creation of two prototypes, namely "Virtual Phone" and "Sky Portal." In the following sections we describe the metaphors in form of sketches and the implementation of the mid-fi prototypes.

3.2 [User-triggered] Virtual Phone

Due to the lack of user-triggered solutions in the design space we iteratively developed the virtual phone solution. Although it was not mentioned by our participants and thus included in the design space, Roo et al. [14, 55, 56] investigated concepts for transferring virtual content from VE to physical objects in RE and Microsoft introduced the flashlight one-directional flashlight [1] to peek into the other reality. However, contrary to their concepts, in ours the virtual phone acts as a tangible window to the other environment. "Tangible window" refers to a physical smartphone that acts as a window to the other reality. Although the user has a tangible smartphone in their hand, the window itself is only visible when triggered by the user, in order to not interfere with the subjective level of presence in VE. It enables users to view the virtual environment while they are in RE (Fig. 1, B) and vice versa (Fig. 1, A). We argue that a familiar metaphor, such as the mobile phone, affords a range of interaction mechanisms that can be adopted for interacting with the other environment. For example, when users want to read a hand-written note in RE while they are in VE, they may peek into RE with the virtual phone and take a picture of the note rather than taking off their headset to do so. Additionally, the virtual phone concept affords interactions users are already familiar with from mobile phone screens, such as zooming in and out of the view, video calling, sharing the screen with others and tapping on bystanders' shoulders when they appear within their view. It is beyond the scope of this paper to implement all interaction concepts that can be adopted. Instead, we will focus on being able to view the other environment and extracting information from it.

3.3 [Continuous] Sky Portal

Motivated by the need to maintain presence whilst enabling a continually available solution, we propose the sky portal. This provides a window to the other – real or virtual – environment in a fixed position above the user (Fig. 1, C for VE view and D for RE view). As the name suggests, within this metaphor we envision the user interacting with it as an entry point into the other environment, and also using it to increase awareness. Peeking onto the portal enables the user to see co-located people from a third-person perspective and increases awareness of the user's own self within the environment they are absent from. This is an improvement on the virtual phone metaphor, in which the user peeks into the other environment from the first-person perspective. By using the sky portal, users instantly know who is in close proximity, which increases their physical integrity. However, compared to the virtual phone, the sky portal does not naturally enable eye contact and sharing information. As one-directional solution and for gradually transitioning between environments, sky portals were initially introduced by Steinicke et al. [9, 68].

3.3.1 Implementation

For the preliminary study, we implemented a mid-fi solution. Our motivation was to understand whether users would be able to seamlessly transition between the environments by using our solutions rather than investigating details of the previously mentioned interactions mechanisms (e.g. zooming into the other environment). As such, the virtual phone was built by attaching a physical camera to a HTC Vive Pro controller rather than implementing a high-fi solution with a smartphone. This maintained the tangibility aspect and allowed the usage of existing buttons to trigger a window to the other environment. In our mid-fi solution the trackpad was used to open the window and the trigger to pick up virtual objects. Similarly, the sky portal was mocked up by using a wide-lens camera mounted to the ceiling of our lab. Visuals from both cameras, ceiling and controller, were streamed into VE. Similarly, the window to VE was built by attaching the camera of the VE scene to the virtual controller object and respectively the virtual sky.

The prototypes are bi-directional, as transitions are made in the same way in both directions: The proposed solutions allow the user to continuously see a window into the *other* environment, thus transitioning between the real environment and augmented reality – window into the virtual environment. It also works in the same way in the other direction from virtual environment to augmented virtuality – window into the real environment. We refer to the latter transitions to Milgram's in-between states [46] as *partial transitions*. To enable transitioning along the whole continuum, which includes transitioning from virtual environment to the real environment, users were able to teleport straight to the other environment. For virtual phone, they had to open the window with a prolonged click on the trackpad. In the sky portal prototype, users had to look at the sky portal, so that the system could track the gaze, and click on the trackpad. When participants returned to VR, they were placed in the same location and direction that they had left. Transitioning from one end of Milgram's continuum to the other extreme end is referred to as *total transition*. Note: The real environment in our exemplary prototype is viewed through the front-facing lens in order to maintain a seamless experience. Using cameras to view the real environment has previously been explored as one-directional solutions [2, 10].

Figure 2 shows an overview of Milgram's MR continuum and our mid-fi prototype solutions for transitioning between the environments. Arguably, A2 may be interpreted as reality-virtuality rather than augmented reality. However, naming it augmented reality supports the differentiations of A2 vs A3 whilst building up on Milgram's conceptualization, as the basis of our work. Figure 3 explains how the user has the same interaction options independent of the reality that they are in – maintaining the bi-directionality.

3.4 Summary

To summarize, in our solutions users seamlessly transition between the real and the virtual environment without taking the headset off. In our mid-fi prototype, we enable this by working with external cameras as well as the HTC Vive Pro dual cameras that are attached at the front of the headset. With this, we propose a continuous sky portal and user-triggered virtual phone solution based on the SeaT-

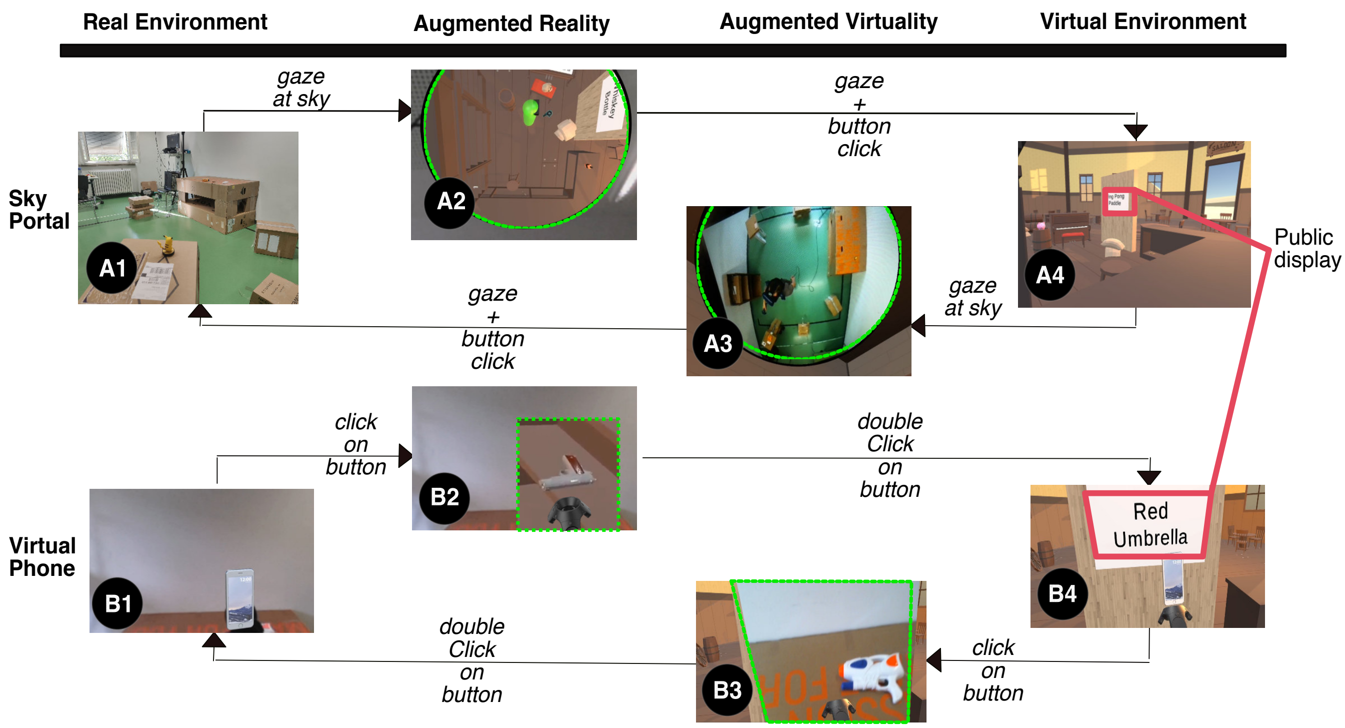

Figure 2: Overview of interaction concepts for virtual phone (A1-4) and sky portal prototype (B1-4) along Milgram's continuum [46]. Interactions are completed in the same way in both directions, enabling bi-directional transitions. The dotted green borders indicate the extent of how the *other* reality is embedded.

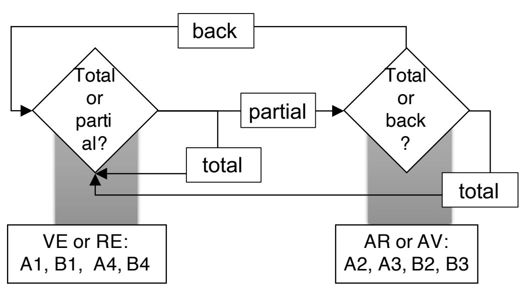

Figure 3: A decision diagram displaying the choice in each of Milgram's realities [46]. Independent of VE or RE, the user has the same interaction options to complete transitions. For partial it is either "gaze at sky"/SP or "button click to view phone screen"/VP. For total it is "gaze at sky+button click"/SP or "double click on button"/SP.

design space, that HMD users can adopt to transition along the MR continuum [46].

4 Study

We conducted a within-subjects lab study (n=36, female=17) to understand how participants interact with seamless bi-directional transition solutions (**RQ2**). The study adheres to the ethical guidelines at our institution.

4.1 Study Design

4.1.1 Setting

To explore the effects of seamless transition between realities, we chose a search-game setting, whereby participants had to transition between the real and the virtual world to find virtual and (Fig.5) physical objects (Fig.4). To enforce bi-directional interactions, objects were alternated, encouraging the user to transition to the *other* environment after successfully finding one object. An object was deemed as successfully found when the user tapped it with their controller.

The study took place in a $5 \times 4m^2$ lab room with cardboard furniture (Fig.2, A1). The virtual room and furniture mirrored the lab room; however, this was motivated by the need for additional places to hide physical objects and to test out how participants handled collisions. The cardboard setup enabled collisions without harming participants. The name of the object to be searched was always displayed in VR on a public display (Fig.2, A4/B4) and virtual and physical objects were equally distributed in the respective rooms. We had three different layouts for the objects in the virtual and physical reality, which were counterbalanced across all participants.

4.1.2 Independent Variables

We introduced one counterbalanced independent variable: *Exemplary prototype*, to differentiate between the solutions, namely the user-triggered *virtual phone* [VP], the continuous *sky portal* [SP] and a baseline *see-through camera* [B], the built-in front-facing cameras of the HTC Vive Pro. The latter is the current standard to view the real world without taking the headset off.

4.1.3 Dependent Variables

To understand the effects of seamless transition, we included the following dependent variables: (a) *search_time*; the time it took participants to find the object after it was displayed to them. Virtual objects were tracked programmatically as they needed to be picked up with the Vive controller, whereas physical objects were manually tracked. The experimenter would press a button as soon as the participant picked up the physical object. In both cases a success audio signal would be given to the participant, to mimic as if both had been tracked by the system automatically. Search time included the time it took to transition. Transitions were developed to take approximately the same amount of time and thus reduced the performance variable to search time and error rate. (b) *error_rate*, the count of items that were not found/only found after a hint after 20 sec, (c) *collision*, the count of collisions with a physical object that was not the target (e.g. cardboard furniture or wrong object), (d) *total_transition*; the count of usage of front-facing camera, (e), *partial_transition*; the count of usage of prototypes. Notably, (d) was measured across all conditions of *exemplary prototype*, whereas (e) was only available for *virtual phone* and *sky portal* – the number of times they turned the virtual phone feature on, as this was user-triggered as opposed to the number of times they looked up. We also included standardized questionnaires, such as NASA TLX [28] for cognitive load, IPQ for presence in VR [59] and SUS for usability [8]. Finally, we conducted a semi-structured questionnaire to gather qualitative data on physical integrity, opportunity for social interactions and general feedback regarding the experience.

4.2 Procedure

The study started by explaining the aim of the study and the data to be gathered. Participants were given the opportunity to ask questions and then they had to sign a consent form to proceed to the study.

To start, the experimenter explained the search game. To mitigate any confusion about the searchable objects, participants were familiarized with them – both virtual & physical – before the start of the study. Next, the HMD setup was introduced and the device was put on for an initial training. In this phase, participants were able to explore the three variations of the exemplary prototypes with no time limit. Once they voiced that they felt comfortable, they were asked to find eight objects (4 from RE and 4 from VE). If an error occurred, the round would need to be repeated. The training lasted until participants had completed one round for each exemplary prototype variation successfully.

For the main part of the study, the procedure was the same. Participants were first introduced to the randomized layout of the study, which they could familiarize themselves with. They were encouraged to find and interact with all virtual and physical objects. Participants had to voice when they felt comfortable to continue.

Before the main game started, participants were encouraged to listen for an auditive disruption – a phone call that appeared on a tablet placed in the physical room – that would come up during their game play. They were shown the tablet, which was placed at the same location for all participants. The auditive disruption was randomly timed for each participant and counterbalanced.

The game started and time was tracked as soon as the first name of the searchable object came up on the public display in VR. Thus, each round started at the same position in VR. The study was completed when participants finished one round of the game for each *exemplary prototype*. Thus, for each round there was only one prototype (baseline, virtual phone or sky portal) interaction available.

At the end of each round – in total three – participants had to fill out the standardized questionnaires. To conclude the study, participants were asked to rate the prototypes and were encouraged to provide qualitative feedback.

4.3 Participants

Participants (N=36, Mean age= 25 (SD=3.03)) were recruited through a university mailing list. Nine had no prior experience and seven used VR weekly. The rest used it less than monthly. Participants received monetary compensation for their participation.

4.4 Limitations

We let our participants start in VE for the search-game. This choice in study design may have influenced in which environment participants felt more present. However, for this explorative study, our aim was to investigate whether participants could use these transition concepts rather than focusing on presence in real vs. virtual environment. Possible effects of the starting position will be reviewed in future work.

The disruptive phone call could have been given through the HMD itself. However, we wanted to imitate an auditive disruption and a phone call sound was deemed to be familiar to most participants.

The resolution of the cameras that we used (e.g. front-facing camera of HTC Vive Pro), may have affected the perception of the RE. Nonetheless, (i) we could not confirm any differences in search times between the worlds, and (ii) participants did not voice a concern on this topic, which suggests that it did not affect their performance.

5 Results

Quantitative results are based on log files from the prototype and the standardized IPQ, SUS and NASA TLX questionnaires. Qualitative results were derived from a thematic analysis of the semi-structured questionnaire. Visual inspection of the density plot and a Shapiro-Wilk's significance test ($p > 0.05$) confirmed that all data, apart from partial transition, was normally distributed, resulting in the usage of parametric tests for statistical analysis. Due to technical difficulties, one participant's data was only partly tracked. Therefore, we had to exclude it for parts of the quantitative analysis.

5.1 Quantitative Results

5.1.1 Search Time and Error Rate (Performance)

A one-way ANOVA, depending on the transition prototype, revealed significant differences for search time ($F_{2,103} = 4,59$, $p < 0.01$). A Tukey post hoc test revealed that average search time for baseline ($Mean = 10.25$, $SD = 1.99$) was significantly faster than for sky portal ($Mean = 12.03$, $SD = 3.28$). We could not confirm any differences for virtual phone ($Mean = 11.43$, $SD = 2.11$).

There were two errors across all participants and all conditions.

Figure 4: Physical objects used for the search-game. Each object was searched for once.

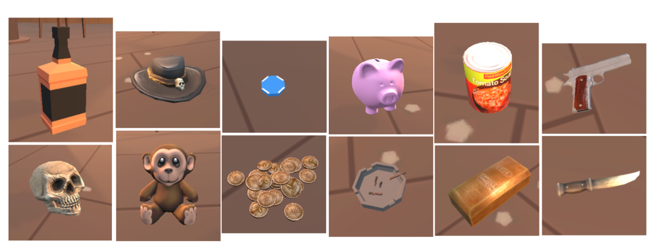

Figure 5: Virtual objects used for the search-game. Each object was searched for once.

5.1.2 Collisions

A one-way ANOVA, depending on prototype, revealed significant differences ($F_{2,105} = 3.16$, $p < 0.05$). A Tukey post hoc test revealed that baseline had significantly less collisions ($Mean = 0.86$, $SD = 0.83$) than sky portal ($Mean = 1.5$, $SD = 1.33$). We could not confirm any differences for virtual phone ($Mean = 1.33$, $SD = 1.33$) and the other conditions. This may be due to the high variance in the data. This difference was also confirmed by experimenters, as observations during study design highlighted that sky portal usage led to disorientation. Participants had difficulty transferring the birds-eye view knowledge to the 3D room.

5.1.3 Transition

A one-way ANOVA, depending on prototype, revealed significant differences ($F_{2,104} = 19.06$, $p < 0.001$). A Tukey post hoc test showed that in the baseline condition there were more total transitions ($Mean = 12.79$, $SD = 4.53$) than in virtual phone ($Mean = 7.91$, $SD = 3.39$) and sky portal ($Mean = 7.88$, $SD = 2.83$). This was expected, as the baseline did not have a an alternative way to access the other environment, compared to the holistic prototypes that had the partial transition options.

Partial transition data was not normally distributed. A Kruskal Wallis test revealed significant differences ($\chi^2(28.59) = 2, p = 0.01$) depending on prototype. Virtual phone ($Mean = 18.61$, $SD = 6.54$) had significantly more partial transitions than sky portal ($Mean = 10.03$, $SD = 4.47$).

A paired sample t-test was conducted to compare the total number of times total transitions vs partial transitions were used within the virtual phone condition. Total transitions ($Mean = 7.91$, $SD = 3.39$) were used significantly less than partial transitions ($Mean = 18.61$, $SD = 6.54$); *t(53)=-8.6, p<0.01*. See figure 6 for an overview.

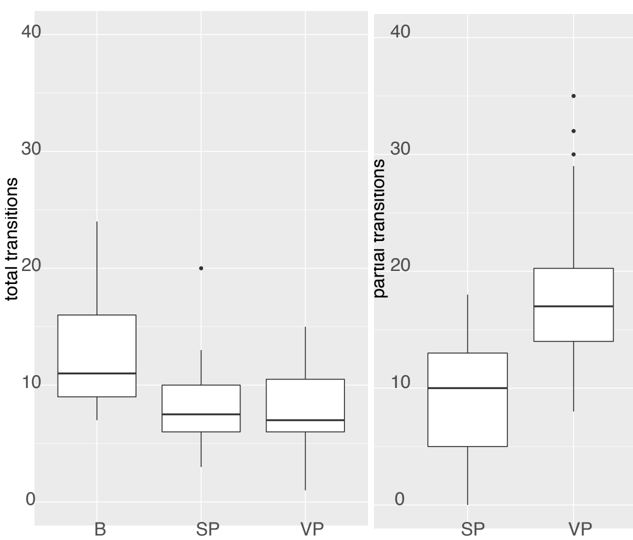

Figure 6: Overview of results on total and partial transfers across all prototypes. Within the virtual phone condition total transitions were used significantly less ($p < 0.01$) than partial transitions.

5.1.4 Standardized Questionnaires

A Friedman Test observed no significant difference ($p > 0.05$) in the overall IPQ scores between baseline (Med = 3.62), virutal phone (Med = 3.5) and sky portal (Med = 3.37). For the overall usability score (SUS) a Friedman Test revealed a significant difference ($\chi^2(2) = 7.41, p = 0.05$) for type of prototype. Baseline (Med = 85) was significantly more usable ($p < 0.01$) than sky portal (Med = 75). No differences were confirmed between virtual phone (Med = 81.25) and the other conditions.

A Friedman Test on the NASA TLX data found no significant difference ($p > 0.05$) depending on type of prototype (Med B = 23.3, Median VP = 26.65, Median SP = 25). However, the subscales highlight significant differences between the prototypes – see Fig.7. Participants perceived sky portal to be more physically demanding than the other two solutions. This was also observed by the experimenters, as participants frequently touched their necks. Virtual phone had comparable results to the baseline condition, however, for mental demand ($F_{2,105} = 3.4$, $p < 0.05$) there were significant differences between virtual phone ($Mean = 3.75$, $SD = 2.4$) and baseline ($Mean = 2.36$, $SD = 1.94$). Nonetheless, participants perceived to have performed as well as for the baseline condition. These findings are also confirmed in the qualitative analysis.

5.1.5 Correlations

To understand how transitions, presence, workload and usability are correlated, we completed Spearman correlations across all variables – see Fig. 8. Due to the space limitations of this paper, only significant numbers are noted in detail. In the baseline condition, presence had a significant negative correlation with workload (rs(105)=-0.35, p<0.05). This means that participants who worked harder had a

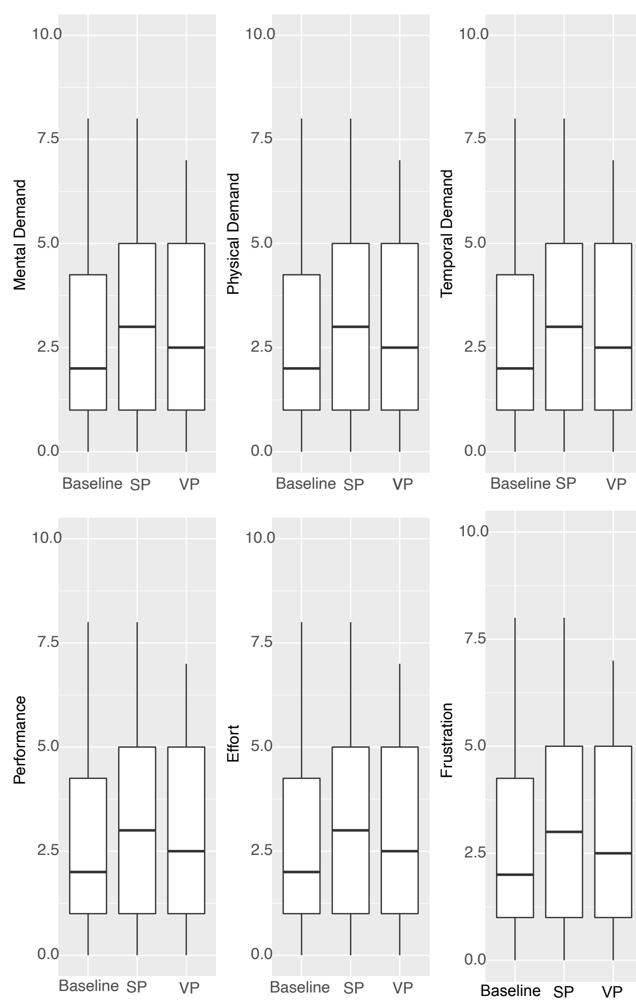

Figure 7: Overview of NASA TLX questionnaire and its subscales.

lower perception of presence. For sky portal, usability had a significant negative correlation with workload (rs(105)=-0.48, p<0.05). Thus, participants who were perceived to have worked harder also scored low on the usability scale. We observed a similar correlation between workload and usability for the virtual phone (rs(105)=-0.44, p<0.05). A significant negative correlation was also found between total transitions and usability. This means that participants who fully transitioned more times into the *other* reality with virtual phone thought it was less usable than participants who used it less. Finally, our data revealed a significant positive correlation between usability and presence. Thus, participants who had a high presence in VR also rated the usability of virtual phone to be high.

5.1.6 Disruption Response

Fifteen out of 36 participants used the virtual phone feature on the tablet, while 11 out of 36 participants used the sky portal. The rest fully transitioned to the real environment.

Finally, we could not confirm significant (i) differences between object layouts and (ii) relationships between collisions vs transitions and search time vs transitions.

5.2 Qualitative Results

The qualitative results confirmed that the virtual phone metaphor was easier to grasp than the sky portal. *"The virtual phone was smooth but with the sky portal I had to think twice where I was in the mirror image." (P 14). "It took time to match my actual position to the one I saw in the portal." (P 7)*

Participants pointed out that the virtual phone felt like a needed addition rather than a replacement of the existing baseline solution. *"The virtual phone felt like an upgrade to the see-through camera [baseline]." (P 4). "I missed being able to peek into the other environment in the other conditions." (P 6).*

The majority of participants highlighted the need to get adjusted to the new systems that they had just tested. *"It takes time to understand the switch [transition]." (P4) "The virtual phone was the most difficult to understand but once I got it [the interaction concept], I found it better than the others." (P 35)*

Participants also provided points (3 for first place, 2 for second place and 1 for third place) for the prototypes. In total, virtual phone received the most points (77), followed by baseline (67) and sky portal (61).

6 Discussion & Future Work

Based on interviews (n=20), we (a) created a seamless transition (SeaT) design space that conceptualizes existing solutions, and (b) completed a user study (n=36) with two exemplary prototypes based on the SeaT design space. Our exploration shows that the virtual phone metaphor has the potential to support HMD users in completing bi-directional transitions and micro-interactions along the reality-virtuality continuum [46] – without performance loss and leaving the reality they are currently in.

6.1 Virtual Phone Was Favoured Over Sky Portal

6.1.1 Virtual Phone as an Upgrade

The virtual phone was comparably usable to the baseline condition. Performance (search time and errors), collisions, presence and usability ratings were similar to the baseline condition. Furthermore, participants used the partial transition option significantly ($p < 0.01$) more often than the total transition one. Participants said it *"felt like an upgrade to the see-through camera [baseline] (P4)*. The significant negative correlation between the usability and workload ratings indicate that prolonged usage and familiarity with the interaction concept may lead to a higher perception of usability. Similarly, there was a significant negative correlation between total transitions and usability. Thus, participants who used the virtual phone more frequently for total transitions thought it was less usable. In the qualitative feedback round, participants said that the *"virtual phone was difficult to understand" (P 35)*, which is why we assume that they did not understand how to use the partial transition interaction for virtual phone and thus used the total transition more frequently at the beginning. For future work, we plan to (i) disable the total transition option for virtual phone and (ii) complete the study in multiple rounds to aid our participants to understand the learning effects better.

6.1.2 Ergonomic Challenges with Sky Portal

The sky portal performed significantly ($p < 0.05$) worse across all dependent variables. We assumed that it would enable higher presence due to its placement in the sky and therefore outside the immediate field of view of the user, but we were not able to confirm this. Participants found the sky portal interaction concept quicker to adopt but had trouble orientating themselves in the mirror image. The quick adoption and frequent usage had both advantages and disadvantages, as we noticed participants rubbing their necks during the sky portal condition. Although they did not voice any neck pain concerns, from an ergonomic perspective this may be a solution that should be used with caution and only in urgent scenarios. Future work may review whether our prototypes are preferred for specific scenarios, such as virtual phone for micro-interactions and sky portal for urgent single usage, such as bystanders coming too close to the HMD user's physical or virtual body [65].

6.1.3 Opportunity for Extending the Exemplary Prototypes

In our exploratory study, we chose to not implement the solution on an actual smart phone but instead mounted a camera on a controller. Despite the constraints of this mid-fi prototype, participants favored the virtual phone interaction compared to the sky portal. They used it significantly more often, and our data suggests that they were faster during the search game and their presence was better.

Participants had difficulty orienting themselves within the room that they were in when using the sky portal and its third person view. This is not only reflected in the quantitative (higher collisions and lower partial transition) and qualitative data but also in the observations made during the study. Compared to the virtual phone, where participants gained confidence in using the feature during the time of the study, the sky portal led to frustration.

For future work, we plan to develop a high-fi prototype of the virtual phone solution – tangible mobile phone instead of a controller – to understand which aspects of existing interaction concepts from mobile phones can be transferred to enable transitions. We also want a solution for the lack of self-awareness and orientation within this metaphor. We noticed that participants turned their virtual phone to view what was behind them, without turning their whole body. Considering the fact that most mobile phones are equipped with two cameras, there may be an opportunity to access both of these as windows to other realities. However, this has to be explored in future work.

6.2 Effects on Tested Variables

6.2.1 Errors in Distance Estimation Resulted in Collisions

We noticed during the study that participants were able to navigate to the appropriate location by using the partial transition function. However, in a small number of cases (approx 1 collision per person), we observed across all prototype conditions that participants were not able to judge the distance to the virtual or physical object. Prior work pointed out out that participants have difficulty estimating distance in virtual environments [11, 15]. This varied greatly among participants in our study, which is reflected in the high variance of our data on collisions. More recently, Roo et al. [54] found that in a seated experience distance estimation is successful. Future work may review how errors in distance estimation can be corrected for

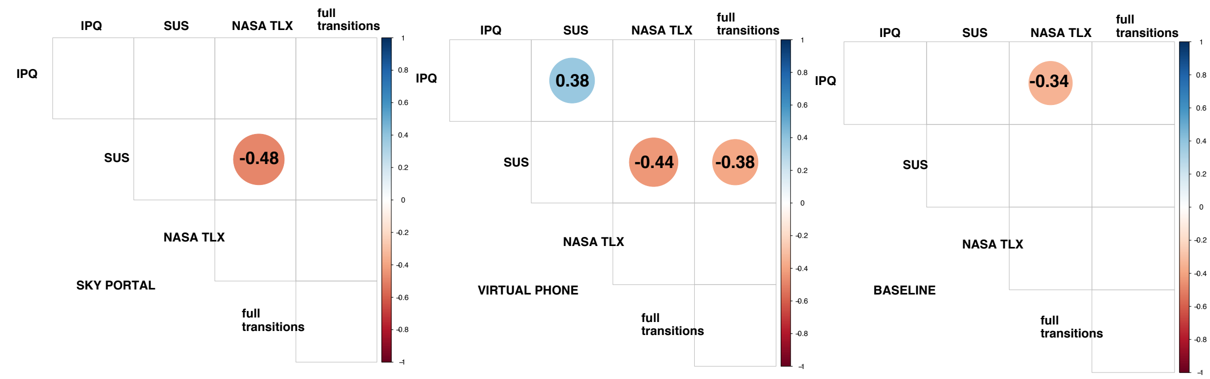

Figure 8: To understand how the dependent variables are correlated, we completed Spearman correlations. The majority of correlations are non-significant, which we ascribe to the high variance in the data.

when transitioning between realities in standing experiences and how users may be supported in doing so.

6.2.2 Towards Optimal Presence

Due to the lack of significant results, we are not able to confirm that partial transitions led to a higher perception of presence than total transitions. However, our data suggests that presence can be high even when partial transition concepts, such as virtual phone and sky portal, are used.

Despite the high variance in our data, there seems to be a potential to use windows to other realities as implicit measures of presence. Careful placement outside the immediate field of view may allow the tracking of how often HMD users *unintentionally* sneak a peek into the other environment and thus are not present in the current environment. This, however, will have to be investigated in future work, as our IPQ data lacked significance and had high variance.

6.2.3 Appropriateness of Success Measures

To measure the success of our exemplary solutions, we chose presence, performance (e.g. search time and error rate) and collisions. With this, we were able to investigate physical integrity & orientation, awareness and interaction with physical & virtual objects. However, the SeaT design space highlights that we were not able to investigate social interaction & collaboration as well as the editing and transitioning of physical objects. Although the quantitative data, specifically the usability score, was similar for the baseline see-through camera and the virtual phone, our qualitative results showed that the latter was more difficult to understand but appreciated more once the interaction concept became clear. Compared to the other solutions, social interaction and & collaboration, as well as editing physical and virtual objects, are already familiar interaction concepts within this metaphor. We believe that adding these requirements and measuring them would influence the perceived value such a solution would contribute from the perspective of an HMD user.

6.3 Design Considerations

6.3.1 Placement of Participants After Transition

In our implementation, when participants returned to the VR scene [from RE], they were placed at the same location that they left. This is a common interaction concept for 3D environments. However, to (i) mitigate errors in distance estimation and (ii) support users' awareness of their own location within a given scene, it may be preferable to place them at a static position. In the RE, when we leave a dynamic room, such as an open office or meeting, we return through an entrance/door. This allows us to adjust to changes in the physical scene, such as a colleague who had stood up to explain something or a physical object that changed location. Transferring this concept to VR would theoretically reduce users' mental load, as they would not have to manage two tasks at the same time, and instead of orientating in the room and adjusting to changes in the scene simultaneously, would only have to focus on the latter when returning to VR.

6.3.2 Adding Bystanders During Micro-Interactions

Our study confirmed that micro-interactions in the reality-virtuality continuum are possible without (i) performance loss or (ii) leaving the reality the HMD user is in. However, our study lacks actual bystanders and thus an exploration of *social interaction and collaboration* – one of the factors in our design space. This was a methodological decision, to narrow the focus of our study. However, adding bystanders may influence the measures that we took, such as presence. Future work may review what effect bystanders have in such a context and whether completing micro-interactions with them collaboratively, such as shaking hands and exchanging notes, has the same effect as picking up virtual and physical objects.

7 Conclusion

In co-located collaborative settings, users are required to transition between the virtual and real environments to complete micro-interactions. In two consecutive studies (N=20 and N=36), we (a) reviewed existing solutions, (b) conceptualized them in form of a design space, and (c) tested two exemplary solutions stemming from the design space. Our exploration shows that our virtual phone metaphor has the potential to support HMD users in transitioning and completing micro-interactions between the reality-virtuality continuum [46] without loss of performance and leaving the reality they are currently in. Our results are valuable for designers and practitioners investigating transitions between realities.

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