Your Place and Mine: Designing a Shared VR Experience for Remotely Located Users

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ABSTRACT
Virtual reality can help realize mediated social experiences where distance disappears and we interact as richly with those around the world as we do with those in the same room. The design of social virtual experiences presents a challenge for remotely located users with room-scale setups like those afforded by recent commodity virtual reality devices. Since users inhabit different physical spaces that may not be the same size, a mapping to a shared virtual space is needed for creating experiences that allow everyone to use real walking for locomotion. We designed three mapping techniques that enable users from diverse room-scale setups to interact together in virtual reality. Results from our user study ($N = 26$) show that our mapping techniques positively influence the perceived degree of togetherness and copresence while the size of each user's tracked space influences individual presence.

ACM Classification Keywords
H.5.1. Information Interfaces and Presentation (e.g. HCI): Artificial, augmented, and virtual realities

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Virtual Reality; Embodiment; Room-scale VR; Social; Dancing

INTRODUCTION
Twentieth century philosopher Merleau-Ponty said humans are fundamentally related to space and based on their capacity to perceive through their body, they make meaning of space [28]. Of all digital technologies, nowhere are the notions of 'being' and 'space' of more consequence than in virtual reality (VR) as characterized by the fundamental concepts of *embodiment* and *presence*. Both 'being' and 'space' contribute to a user's sense of presence defined as ''...the strong illusion of being in a place in spite of the sure knowledge that you are not there'' [36].

A user is immersed in VR in two ways: first, through the representation of computer generated surroundings displayed from a first person point of view, and second, through a match between proprioceptive signals about the movements of their body with those of a corresponding virtual body [39]. In practice, a virtual body is often replaced by disembodied hands, which creates a conflict between proprioceptive data which tells the user their body is there, and sensory data in VR where the body does not exist. Embodiment is an attempt to reduce the conflict by providing a body representation where virtual body movements correspond with real body movements [36]. Studies have shown that reported presence is higher if the match between proprioception and sensory data is high [38, 40]. Because of this match, natural walking is a desired feature in VR applications [50], and has repeatedly been shown to be superior to other navigation methods such as flying or using game controllers [41, 50].

Embodied social VR can help realize the utopian environment where distance disappears and we interact as richly with friends, family, and colleagues around the world as we do with those around us. This could also allow us to have natural interactions with those who cannot travel to meet physically. In order to create such rich experiences, there are certain challenges we need to overcome. Room-scale VR systems allow users to freely walk around in a designated tracking area with their body positions translated into VR in realtime, thereby supporting natural movement in VR. Taking advantage of

Figure 1: Participant 1 (top, male) in their physical and virtual space respectively, waving at participant 2 (bottom, female) in a different physical space, who waves back. To support shared virtual spaces for geographically distributed participants in room-scale setups of different sizes, we created three physical-to-virtual space mapping techniques.

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natural movement afforded by room-scale VR, co-located room-scale VR experiences can allow all users physically located in the same tracking space to move around naturally in a shared virtual space. However, when users are remotely located, each user inhabits a different physical space. All the different spaces need to be mapped to a shared virtual space to can allow remote users to interact in close proximity.

In this paper, we present three approaches for mapping users' physical spaces to a shared virtual space for remote users to interact in virtual proximity. Our goal is to create experiences where users interact as richly over distance as they do with those in the same room. Our approach is novel in that prior work supporting multiuser interactions in VR does not take into account the size and shape of each individual user's tracking space. By mapping the different room-scale spaces into a single shared virtual space, our system allows each user to move in the shared virtual environment by walking in their physical space.Since walking has been shown to be the most natural form of virtual locomotion and consistently elicits higher presence than other navigation techniques [50], supporting natural walking was one of our design goals. In our study setup, two remotely located users with full body tracked avatars (see Figure 5) get a dance lesson together in VR. The lesson takes place in a park environment where a group of virtual onlookers also copy some of the instructors' dance moves (see Figure 3) presented during the lesson. We chose a dance lesson as our social scenario because dancing together affords natural exploration of space and body-based interaction, as opposed to tasks like modeling a car or city planning [49] that center around hand-based interactions. Prior research in virtual dance lessons has mostly focused on the analysis of a single user's whole body motion through different motion capture techniques [8, 18].

Our user study reports on the implications of three different strategies for mapping two physical tracked spaces to a single shared virtual space, namely *Scale*, *Kernel*, and *Overlap*. The different space mappings afford different activities and movement patterns. Our results show that partially or completely overlapping two spaces of different sizes allows for experiences with high levels of copresence. Adding a translation gain to the movements of a user in the smaller space allows them to access a shared virtual area as big as the larger space in the Scale mapping technique. However, this mapping technique showed to be the least preferred.

To the best of our knowledge, this paper is the first of its kind to report on the effects of spatial mapping strategies that support embodied multiplayer interactions for remotely located participants in room-scale VR.

The key contributions of our work for remotely located multiuser room-scale VR systems are the following:

1. Three novel physical space to shared virtual space mappings, and their associated trade-offs.
2. Insights from a user study ($N = 26$) exploring the impact of physical to virtual space mappings on presence, copresence, social interaction, and togetherness.
3. Four design guidelines for creating shared virtual spaces for remotely located users. These are derived from our experience and analysis of the user study results.

RELATED WORK

The work presented in this paper explores the influence of space mapping techniques on social interaction in a VR scenario where users are geographically distributed and have avatars that they can fully control through their own body movements. We summarize below a few most directly related works in areas of proxemics, the relationship between proprioception from real walking and corresponding visual feedback in VR, and multiuser or social VR experiences.

Proxemics

In an influential paper, Hall categorized interpersonal space into four zones of intimate, personal, social, and public distances that people maintain towards each other in the real world [19]. People adhere to similar norms in VR, keeping greater distances from humanoid avatars than cylinders [1]. Participants moved out of the way when approached by virtual avatars and also kept greater distances when there was mutual gaze [2]. Other studies have also shown that real world proxemics behaviors work similarly in VR [17, 52]. Skin conductance response was shown to vary with the distance of one or many virtual characters as expected on the basis of proxemics theory [26]. While face-to-face interaction generates the most vivid sense of copresence [14], the feeling of being in the same place with others is enhanced by embodiment [54]. The experience of ''togetherness'' in our dance lesson experience is facilitated by close interpersonal interactions made possible by physical to virtual space mapping, real walking for locomotion, and full body tracking.

Proprioception

Walking is a basic form of interaction with the real world and similarly fundamental and desirable in VR [22]. Studies have found that real walking is significantly better than both walking-in-place and flying in terms of simplicity, straightforwardness, and naturalness of locomotion in VR [41, 50]. Research shows that a proprioceptive match between real and virtual body movements can enhance presence [39, 42]. These findings have led to research that supports walking through the development of tracking systems so users can move about in the physical space [51] and the building of mechanical walking devices such as treadmills, roller skates, and foot plates [7, 9, 22, 23]. Recently, walking in VR has been made possible for consumers through room-scale tracking included with the HTC Vive and mechanical devices like the Virtuix Omni[1]. Presence in VR is impacted by perception through the visual, auditory, and kinesthetic senses. Subjective presence is significantly correlated with the degree of association with a virtual body which suggests that substantial presence gains can be had from tracking all limbs and customizing avatar appearance [50]. Natural body movements in VR also provide improved task performance [32], and benefits for memory and cognition [53]. Our system is designed to support two

[1] http://www.virtuix.com/

users with different tracked space sizes. The mapping techniques allow virtual movement through physical walking, and embodiment affords natural interactions in the shared virtual space.

Multiuser VR

The first established work where more than one person could simultaneously inhabit the same virtual world was called 'Reality Built for Two', proposed in 1990 [6]. Following this, several other systems were created for two or more users [13, 15] and today, support for online multiplayer systems is fast becoming commonplace. Outside the home, VR entertainment centers (The VOID or VRcade) provide playful experiences in warehouse-size spaces to multiple users simultaneously while allowing natural walking for locomotion. Another type of multiuser system is device-based asymmetrical VR where a VR user interacts with one or more non-VR users who may be in the same physical space or remotely connected through a PC or tablet [16, 44]. SnowballVR creates a space-based asymmetrical VR experience where the size of the tracked area is used to assign appropriate roles to each user [44]. Social VR applications like *Facebook Spaces* and *AltspaceVR* allow people from around the world to participate from seated or room-scale setups respectively. Neither of these social VR systems support full body tracking such as presented in Metaspace [45] for co-located users. Our system supports full body tracking for remotely located participants using off the shelf trackers. It does not require expensive motion capture suits or tracking systems which are the norm for full body tracking. We show that physical interaction supported by full body tracking and embodiment enables realistic behaviors in VR.

Collaborative Virtual Environments

Collaborative Virtual Environments (CVEs) involve the use of networked virtual reality systems to support group work [4, 49]. The key concept behind CVEs is that of shared virtual worlds whose occupants are represented to one another in graphical form and who interact with each other and with the virtual environment [10]. Oliviera et al. presented an early example of asymmetric collaboration where a VR user received guidance and instruction from a PC user [30]. CVEs do not necessarily need to reflect or embody the characteristics of conventional environments to enable them to support particular forms of activity or interaction [11, 40]. It has previously been shown that presence in VR is related to what the users can do and less so with the visual fidelity of the environment [37]. Our system uses a collaborative dancing lesson to facilitate social interaction.

SYSTEM DESCRIPTION

This paper investigates social interaction for a geographically distributed set of two users. The designed experience requires proximity afforded through a mapping of each user's physical space to a shared virtual space. To examine distinct physical to virtual space mappings, we implement the task of taking a VR dance lesson. This section starts by defining some terminology. We present four design goals and describe three space mapping approaches that we implemented. We follow with a description of the dance lesson application.

Terminology

- **Virtual environment or world** is the virtual space that is much larger than each user's tracked space.
- **Room-scale** is a type of VR setup that allows users to freely walk around a tracked area, with their real-life motion reflected in the VR environment.
- **Physical space or tracked space** is the real world area in which a user's body position and movements are tracked by sensors and relayed to the VR system.
- **Shared virtual space** is an area in the virtual world where remotely located users can 'come together' to interact with one another in close proximity. The shared area can be as big as the largest tracked space depending on the space mapping technique used. Each user can walk to and in the shared area by walking in their own tracked space.
- **Presence** is defined as the sense of ''being there.'' It is the ''...the strong illusion of being in a place in spite of the sure knowledge that you are not there'' [36].
- **Copresence**, also called ''social presence'' is used to refer to the sense of being in a computer generated environment with others [5, 35, 12, 34].
- **Togetherness** is a form of human co-location in which individuals become ''accessible, available, and subject to one another'' [14]. We use togetherness to refer to the experience of doing something together in the shared virtual environment.

  While it is easy for multiple participants to be copresent in the same virtual world, supporting proximity and shared tasks that can elicit a sense of togetherness is much harder.

Design Goals

We outline a series of goals for our system inspired by [15] to enable remote social VR systems that allow for more natural experiences than currently available. Specific design goals of our system include:

Spatial Connection: supporting natural and realtime interaction between participants from different locations, and direct perception of others through their positions and orientations.

Space Heterogeneity: allowing users with different room-scale setups to interact within a shared virtual space.

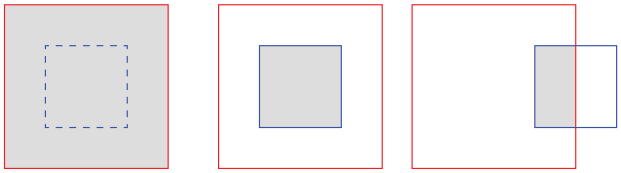
Identity: using humanoid avatars with visuo-motor synchrony between the real and virtual bodies to support realtime interactions and natural behaviors similar to the real world.

Activity Diversity: supporting different activities that involve movement in space with occasional physical proximity (e.g., training, learning, creating).

Space Mapping

We designed and implemented three approaches for mapping two physical spaces of different sizes (L: $4m \times 4m$, larger space; S: $2m \times 2m$, smaller space) to a shared virtual space. These sizes were informed by 1) the most common quadratic play area as reported by the popular consumer VR platform [46], and 2) by the largest allowed play area for the

HTC Vive. The size of the shared space differs in each configuration but it does not prevent each user from using the entirety of their own tracked space for non-shared activities.



(a) (b) (c)

Figure 2: The three physical space to shared virtual space mapping techniques we designed: (a) Scale, (b) Kernel, and (c) Overlap. The red outline shows the larger physical space (L) and the blue outline shows the smaller physical space (S). Shared virtual space is shown in gray.

Scale stretches the smaller space to match the size of the larger space (see Figure 2a). This requires scaling the user's movements in the smaller space by a factor of L/S. A user in space **L** will thus find the user in space **S** moving twice as fast as normal while the user in **S** will find the user in **L** moving at a normal speed. The shared space coincides with the entirety of each user's tracked space. The area of the shared space equals that of the larger space for the two spaces R_1 and R_2; $max(R_1.size, R_2.size)$.

Kernel places the smaller tracked space in the center of the larger tracked space (see Figure 2b), making the shared virtual space coincide with the entirety of the smaller physical space. The user in **L** can walk around freely in their space but close interactions with the other user are limited to the shared space. The area of the shared space equals $min(R_1.size, R_2.size)$.

Overlap places the two tracked spaces next to each other with half of the smaller space overlapped with the larger space (see Figure 2c). This results in a shared space that coincides with half of the smaller tracked space. This is the smallest shared space of the three with an area of $.5 \times min(R_1.size, R_2.size)$.

Table 1 shows the virtual space as created by the different space mapping techniques and specific employed room sizes in our user study.

	Union space	Shared virtual space
Scale	16 m^2	16 m^2
Kernel	16 m^2	4 m^2
Overlap	18 m^2	2 m^2

Table 1: Union is the area of the combined physical space in each mapping configuration. The shared virtual space size varies with mapping technique resulting in the largest for Scale and smallest for Overlap.

Environment and Activity

Our goal was to find a collaborative activity that would address our design goals, namely a multiuser activity where spatial factors between people would determine the social dimension of the activity. We also wanted an environment where users could freely choose to engage with each other socially such that there would be no wrong way to use the system.

We created a virtual city park (see Figure 3) with a small creek, trees and picnic benches. Users were placed in the center of an open area in the park. A few virtual characters were placed in a circle around the users. Each user could see the boundary of their tracked space but could not see the other person's space boundary nor the shared space outline. This prevented any confusion about where the user should stay or move to and allowed for more natural interactions.

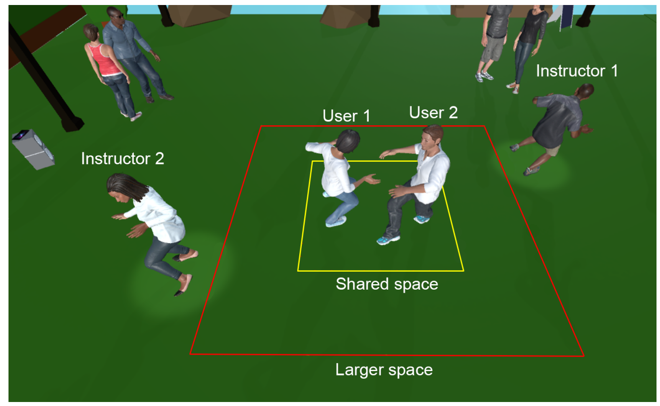


Figure 3: The dance lesson park setting as seen from a 3rd person point of view. The figure shows two users dancing together in the Kernel mapping technique, each with their own instructor in the spotlight who is facing away from them. The brightness of lights in the park has been turned up for the image though in the actual experience the lights are dimmed down which makes the spotlight stand out (see Figure 4).

We implemented a dance lesson experience. Each user had a personal dance instructor visible only to them and placed behind their dance partner (Figure 3). The instructor had its back facing the user to make it easy to follow dance moves (see Figures 3 and 4). Instructors were identifiable by a spotlight on them, their facing direction and their location in the scene which were different from all other characters. Users could choose to follow their instructor or improvise with each other.

Figure 4: Users copying their instructors' dance move. Top: Male user in tracked space (left), and his corresponding VR view (right). His dance instructor is shown in the spotlight behind the female participant. Bottom: Female user in tracked space (right), and her corresponding view (left). Her instructor is visible in the spotlight, behind the male user.

The lesson consisted of two *routines*; each routine comprised of four *dance moves*, done for around 10-15 seconds each, with a small break in between. The dance moves required users to move their arms or move their body and were designed to make the users come closer on occasion without requiring them to touch one another. The four dance moves were:

1. *Wave*: moving the body like a wave, from right to left.
2. *Push-the-roof*: both arms in the air moving up and down.
3. *Forward and backward*: moving two steps forward, and two steps backward.
4. *Sidestep*: taking two steps sideways to the left, and two to the right.

Body Tracking

Each user's body was tracked using a combination of three Vive Trackers[2] placed one on each foot and one on the lower back, two hand controllers and the HMD, along with an inverse kinematics system to create a realtime motion capture setup. The tracked points and the inverse kinematics system together create a system that provides real-time visuo-motor synchrony, between the real and the virtual body, which is considered one of the primary reasons for presence in VR [33, 48]. Users were represented as size and gender matched humanoid avatars with visuo-motor synchrony between the real and virtual bodies (see Figure 5).

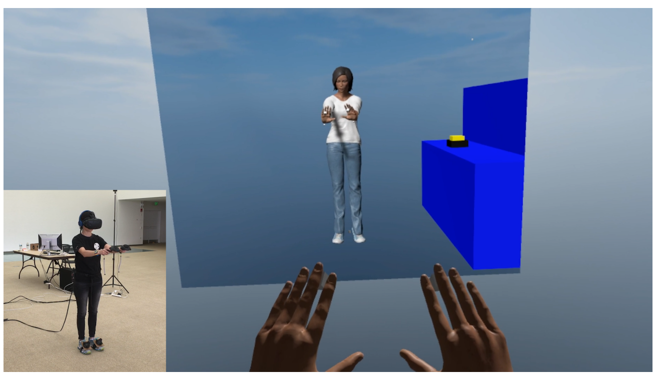


Figure 5: Before entering the park, participants go through an embodiment phase. Inset shows a participant in the physical space with Vive trackers on their feet and body; rest of the figure shows the participant's perspective. A mirror provides a full body view.

The hand controllers provided haptic feedback upon collisions with the other user's virtual body for an additional sense of awareness of the other person's location in the virtual space. This was especially useful in the *Scale* mapping because of high possibility of collisions due to user movement scaling. Research also shows that users consistently underestimate the spatial dimensions in VR [20]. Anecdotally, a few subjects mentioned that despite the avatar matching their height and arm span, it seemed bigger and the tracked space felt smaller in VR than in real life.

EXPERIMENT

We ran a user study to compare the three space mappings and to understand the fundamentals of embodied social VR from the users' perspectives.

[2] https://www.vive.com/us/vive-tracker/

Participants

We recruited 28 participants who were mainly local students. We paired participants in groups of two (14 groups) based on the time slots they requested; three groups consisted of participants who were familiar with each other. Nine participants were female; the average age was 20 years. Most participants had little to no previous experience with VR ($M = 2.0$, on a scale of 1-to-7; 1 being no experience, 7 being very experienced). One group (two participants) was discarded due to bad body tracking distorting the embodiment; the resulting analysis is done on 26 participants (13 groups). We reimbursed participants the equivalent of $10 USD, for one hour of participation.

Apparatus

We had two identical HTC Vive setups consisting of two base stations, an HMD, two hand controllers and three trackers, connected to a desktop PC (Windows 10; 16GB RAM; GEFORCE GTX 1080Ti). To increase mobility of participants we extended all cables by $3m$. To reduce network latency, the PCs were setup on a LAN connected with ethernet cables. We created the VR system in Unity with FinalIK for inverse kinematics. The 3D models were downloaded from the Unity Asset store and animations from Mixamo.

Task

We wanted to study social aspects in VR using a task that allowed us to compare participants' movements across different space sizes and mappings. We sought a multiuser task with a fixed progression to allow for assessment of both individual and collaborative performance. Unlike many collaborative tasks, choreographed dancing provides a proposed trajectory that allows for an objective assessment of both individual and collective effort. Dancing has previously been used in HCI to reason about embodied aspects of interaction design [25].

We intentionally chose not to employ common collaborative tasks such as a puzzle, or model building, since these seldom use room-scale movements or require body movements. Tasks like attending a lecture or viewing data visualizations together have been explored in prior work as collaborative VR tasks where multiple users are present in the same virtual space looking at the same thing together [29]. Our task is similarly collaborative as both users are in the same virtual space dancing together. Some dance moves are performed together, i.e., participants approach one another while facing each other, while other dance movements are performed independently but in proximity.

The choreography consisted of four different moves (wave, push-the-roof, stepping forward and backward, and sidestepping). While participants were encouraged to dance together, each participant had their own dance instructor, located behind the other participant, showing how to perform each move. Music accompanied the choreography. Each trial required participants to perform the choreography twice, matching the length of the music. Each trial lasted about 4 minutes, the length of the song (1 trial = 2 rounds $\times$ 4 dance moves $\times$ 15 seconds, excluding breaks). The total duration of the study was one hour per group, with three trials and questionnaires filled out after each trial.

Data Collection

We collected different types of data (see full list in Table 2):

Tracking. We recorded all raw position data for all sensors.

Interaction. We recorded collisions between avatars.

Self-report. Participants answered questionnaires about presence, togetherness, and social presence, three times each; once after each trial.

Design

The study was a mixed-design experiment with two independent variables: room size, administered between-subjects, and space mapping technique, administered within-subjects. All groups did three trials, one for each space mapping. The order of the trials was counter-balanced using a latin-square assignment. Dependent variables came from movement patterns and self-reports (see all dependent variables in Table 2).

Room Size

We manipulated the physical tracked room size as an independent variable to observe differences across space mappings attributable to the size of the room. We employed two different room size configurations: $2m \times 2m$ and $4m \times 4m$. One participant from each group was placed in the smaller space and the other one in the larger space.

We disabled the chaperone system (the blue 3D safety grid that warns users as they approach the tracked area boundary) but made each user's tracked space visible in VR with a green outline on the ground. The virtual park environment was identical for each user in both room sizes.

Space Mapping

All groups did a trial with each of the different space mappings (Scale, Kernel, and Overlap), in counter-balanced order.

Procedure

Participants were recruited using an internal email list and signed up for our experiment online in groups of two. After signing a consent form, participants were asked to read a short background story that fit the environment and task. Following that we attached the Vive trackers and helped the participants put on the HMD.

The experience was divided into two scenes. The participants went through an embodiment phase in the first scene where they stepped into the body of an avatar and spent a few minutes getting comfortable with the idea that moving their own hands or legs resulted in corresponding body part movements in their embodied avatar. Once satisfied, they pushed down on a big yellow button in the scene which took them to the park. At that point the two VR systems were connected and participants could see each other's avatars in addition to everything else in the park. Audio instructions were provided upon entering the park scene, and also during the experiment to tell the participant when to switch dance moves. An evaluator carried the cable behind each participant from a safe distance, making sure that it did not interfere with the participant's movements.

Participants spawned in the center of the shared space, one after the other. A yellow cross showed both participants where to walk to, before the dancing started. The crosses were placed close to the outer bounds of the shared space in a way that made the participants face each other, one meter apart.

Participants were asked to dance with abandon as an experimenter managed the cables to prevent tripping. We conducted the study in an open space with no physical obstacles so there was no fear of running into objects either. Most all participants danced freely, with observable playfulness in friend pairs who tried different movements in addition to following their dance instructors.

RESULTS

In this section we report on the insights from our study. We organize the results by dimensions from Table 2. We employed 5 dependent variables, with a total of 13 statistical tests.

Presence

Presence is defined as the sense of *being there* [42]. Presence was determined using the questions from the SUS-inventory [40] presented in a random order after each trial. The scores reflect how many questions (out of four) were answered with a score of 5 or higher (on a scale of 1-to-7) [27]. A score of 2 thus means that a participant reported a high score (≥ 5) on two of the four protocols in the questionnaire.

Room Size

We treat the SUS count as binomially distributed for a logistic regression on group (as in [27]). We found a significant difference for presence on room size ($\chi^2 = 3.97$ on 1 df, $p < .05$); the larger physical space created a higher sense of presence (see Figure 6).

Dimension	Source	Data			Measures
Presence	SUS [40]			S	Presence measures.
Togetherness	Basdogan et al. [3]			S	Sense of being together measures.
Copresence	GEQ (Social Presence Module) [21]; Jakobsen & Hornbæk [24]			S	Social presence measures.
Movement and use of space	Jakobsen & Hornbæk [24]		T	S	Movement patterns, VR sickness.
Interference and conflicts	Jakobsen & Hornbæk [24]	I	T		Collisions and conflicting actions.

Table 2: The investigated dimensions and their associated measures and analysis methods: Tracking data, Interaction data, Self-report.

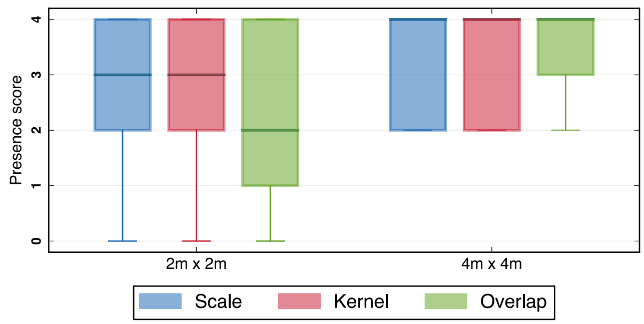


Figure 6: Presence scores divided between room size and space mapping. Room size significantly alters presence in VR, while the space mappings provide consistent levels of presence. Thick horizontal lines show medians, and the boxes represent interquartile ranges.

Space Mapping

We found no significant difference between space mapping techniques on presence; $\chi^2 = 0.35$ on 1 df, $p = .84$.

Summary

The results show that larger tracked areas lead to higher perceived sense of presence, even if the virtual spaces are otherwise identical. We also show that participants perceive comparable sense of presence regardless of the employed multi-room space mapping technique.

Togetherness

Five questions on the sense of being together (from [3]) were placed in random order in the questionnaire administered after each trial; each question was rated on a 1-to-7 scale. Table 3 shows the mean score for each question, and a togetherness score (1-to-5), computed as the number of questions (of five), which had a 'high' response (≥ 5). A Cronbach's alpha shows the internal consistency of the inventory.

	Scale	**Kernel**	**Overlap**
Sense of being with another person	4.5	5.3	5.2
You were not the only one involved	4.0	4.2	4.3
You and your dance partner danced together	3.3	4.0	4.5 *
A real experience of doing something together	4.3	4.5	4.9
Another human being interacted with you	4.2	5.2	4.9
Togetherness ($\alpha = .85$)	**2.3**	**2.9**	**3.0**

Table 3: Mean scores for items in the togetherness inventory. Scale scores consistently lower than the other space mappings. The scores that showed significantly different from Scale with a Wilcoxon rank-sum test on .05 are shown with *.

Room Size

Room size did not impact the degree to which participants had the sense of being together; togetherness for $2m \times 2m$ was $M = 2.5$ ($SD = 1.6$), and for $4m \times 4m$ it was $M = 2.9$ ($SD = 1.8$). A logistic regression for togetherness on room size showed as not significant, $\chi^2 = 0.65$ on 1 df, $p = .42$.

Space Mapping

Kernel and *Overlap* showed very similar degrees of togetherness (see Table 3), no significant differences were shown for any items between *Kernel* and *Overlap*. *Scale* consistently scored lower on all items compared to *Kernel* and *Overlap*. While only two of these were significantly different (and only for Overlap vs Scale), we believe that the scores together show that *Scale* is less optimal for experiences requiring high degrees of togetherness, and that *Kernel* and *Overlap* offer comparable degrees of togetherness.

Summary

We did not find a correlation with the size of a person's tracked space and the perceived degree of being together with another person in VR.

On the contrary, the employed space mapping technique seems to have an influence on the degree with which participants feel together. Scaling scores lower on all items in the togetherness inventory, one which showed significantly different on 0.05. *Kernel* and *Overlap* appear comparable in terms of togetherness, even if Kernel had twice the shared virtual space, and Overlap had a larger union virtual space.

Social Presence

Five questions on social presence (from [21, 24]) were presented in a random order in the questionnaire administered after each trial; each question was rated on a 1-to-7 scale. Table 4 shows the mean score for each question, and a copresence score (1-to-5), computed as the number of questions (of five), which had a 'high' response (≥ 5). A Cronbach's alpha shows the internal consistency of the inventory.

	Scale	**Kernel**	**Overlap**
I knew what my dance partner was doing	4.3	5.3 *	5.4 *
My dance partner knew what I was doing.	4.2	4.8	5.1
I felt connected with my dance partner.	3.5	4.6 *	4.5 *
What my dance partner did affected what I did.	3.7	4.2	4.3
What I did affected what my partner did.	3.5	4.0	3.9
Copresence ($\alpha = .93$)	**2.0**	**2.9**	**2.8**

Table 4: Mean scores for items in the social presence inventory. Scale scores consistently lower than the other space mappings. The scores that showed significantly different from Scale with a Wilcoxon rank-sum test on .05 are shown with *.

Room Size

Room size showed to have no significant effect on social presence experienced by the participants; copresence for 2×2 was $M = 2.3$ ($SD = 2.1$), and for 4×4 it was $M = 2.8$

($SD = 1.9$). A logistic regression for copresence showed no significant effect on room-size, $\chi^2 = .76$ on 1 df, $p = .38$.

Space Mapping

We found no significant differences between Kernel and Overlap on social presence. Scale, however, showed lower average scores on all items in the social presence inventory compared to the two other methods (see Table 4). For two of the questions, these differences were significantly different on .05 between Scale and the other methods, shown with a Wilcoxon rank-sum test.

Summary

We found no differences on social presence attributable to room size, while we found differences attributable to the space mapping technique.

Interestingly, this finding is the inverse of (single-person) presence; our findings suggest that the degree of being present in VR alone is mostly altered by the available walking space, while the social dimension of being in VR with another person is to a larger degree controlled by how the virtual shared space is mapped and what it affords.

Movement and Use of Space

We looked at the raw tracking data to assess how factors relating to the use of space changed across experimental conditions. We merged the data from the two VR stations, such that the potential data loss due to networking would not affect the logs.

Distance Traversed

We looked at which space mapping caused the greatest traversed distance in the virtual world. Figure 7 shows that, except for Scale, people in larger spaces move around more ($F(1,75) = 11.3, p = .001$); it also shows that Scale caused less overall movement. We speculate that scaling movements makes locomotion less desirable, and thus affects users' movement patterns. Walked distances in the real world can be upscaled by 26 percent, when they are mapped to virtual motions [47]. In the Scale mapping technique, user movements were upscaled by 100 percent, much higher than the formerly established imperceptibility threshold. Movements in VR that do not correspond to equivalent real world movements can cause a visuo-vestibular conflict which is believed to cause motion or VR sickness [31].

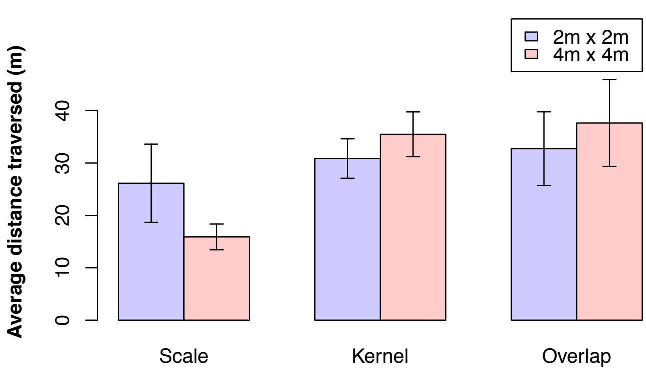


Figure 7: The mean distance traversed split into space mapping and room size. Error bars show standard deviation.

Raw Movements

Figure 8 shows the aggregated virtual movements visualized for each space mapping technique which reveals some notable trends. As evident in Figure 8a, contrary to expectations, Scale participants in the $4m \times 4m$ space moved much less than those in the $2m \times 2m$ space. Compared to the other two techniques also, participants in the larger space moved much less than participants in the smaller space in the Scale mapping. This is likely to avoid collisions because of unpredictable movements of the person in the smaller space, resulting from a translation gain of 1.5. This is possibly also the reason why we see low copresence scores for *Scale*.

Kernel (Figure 8b) shows the shared space to be inhabited primarily by the user in the small space, even if the person in the larger space is unaware of the boundary of the shared space; roughly half of the positions of the person in the larger space are observed in the shared space.

Overlap (Figure 8c) shows surprisingly little proximity between users; the small space user almost exclusively inhabits the shared space. It also seems to condense movements to a more fixed space (along the x-axis), compared to the other space mappings. Additionally it can be seen that the person in the smaller space overstepped the actual boundary (which was possible due to the lack of physical walls); this could have shifted all activity towards that direction.

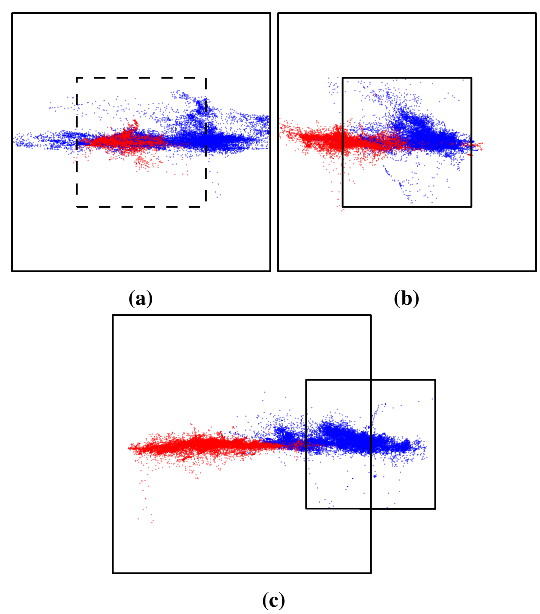


Figure 8: Raw virtual positions for all participants. Black borders show the large and small tracked spaces for both users. Blue observations show positions of participants in the smaller room; red observations are from participants in the larger room. Figures show how movement differed across the space mappings: (a) Scale, (b) Kernel, and (c) Overlap.

Distance Between Participants

We computed the average distance between the two virtual avatars throughout the entire study: Scale $1.01m$ ($SD = 0.36$), Kernel $1.09m$ ($SD = 0.31$), Overlap $1.92m$ ($SD = 0.29$).

Overlap caused significantly more distance between users; $F(1,76) = 68.2, p < .001$; due to the smaller shared space and the larger combined space. Scale and Kernel showed similar proximity between users' avatars; $F(1,50) = .4, ns$.

Table 5 shows how much time participants spent in different proxemic zones, as defined by Hall [19]; intimate (0-46cm), personal (46-120cm), and social (120-240cm). We note that Scale affords the most intimate interaction; Kernel mostly personal; and Overlap mostly interaction in the social zone.

Because we disabled the chaperone system and conducted our study in an open space without walls to prevent any accidental collisions with obstacles, users were able to walk outside of their virtual spaces. This however only happened to a small extent, and almost exclusively for Overlap (see Figure 8).

	Intimate	**Personal**	**Social**
Scale	24%	35%	41%
Kernel	9%	51%	40%
Overlap	2%	11%	87%

Table 5: Time participants spent in different proxemic zones.

VR Sickness

Participants in our study experienced very low VR sickness; on a scale of 1-to-7 on the question *How dizzy, sick or nauseous did you feel resulting from the experience, if at all?*, $M = 1.46$. Using an ANOVA we found no significant difference on room size; $F(1,75) = .59, p = .45$. We also found no significant difference on space mapping; $F(1,75) = .02, p = .88$.

Summary

We observed several differences in movement patterns due to both room size and space mapping technique; larger rooms cause more movement; Scaling causes little movement (especially by users immersed in the larger space); With Scale, users have the most intimate interaction; using the Overlap mapping causes larger distance between users. The participants overstepped the boundary to a very limited degree.

Interference and Conflicts

We provided participants with vibrotactile feedback through the hand controllers upon collisions between the avatars. That way participants were informed about bumping into each other even if it was not visually clear to them. Here we report movement conflicts defined as the average number of collisions between avatars lasting longer than 1 second. Our records show that, as expected, Scaling causes more conflicts than the other space mappings; Overlap causes the fewest: Scale $M = 5.0$ ($SD = 6.7$); Kernel $M = 1.0$ ($SD = 1.8$); Overlap $M = 0.1$ ($SD = 0.4$). These results reflect Hall's zones of interaction [19] and confirm previous findings about users exhibiting real world proxemics behaviors in VR.

DISCUSSION

Here we summarize our main findings, with a discussion of design implications for remotely located social VR experiences. Additionally, we provide some unanswered questions that can pave the way for future research directions.

The goal of our study was to examine the impact of space mapping techniques on copresence, social interaction, and the sense of being together for remotely located participants in room-scale VR setups. Even if no significant differences were found for copresence based on each user's tracked space size, we found differences in copresence between the three mapping techniques. Scale showed significantly worse than the other two techniques. We believe this may have been due to unpredictable and unnatural movement of the person in the smaller space (moving at 2x speed) as visible to the person in the larger space. Some participants remarked upon how the shared virtual space in Kernel (2x2m) felt crowded with two people while they felt comfortable sharing a similarly sized space with another person in the real world. The avatars were scaled to match each participant, so this difference in spatial perception and its resulting impact on proxemics may be due to factors unrelated to proprioception and warrants further exploration.

Similar to copresence, the sense of being together was not influenced by the size of the tracked area but the mapping techniques did influence the perceived sense of togetherness. In contrast, individual presence was dependent on each user's tracked space size and did not change between the mapping techniques. Even though Scale was found to be an undesirable mapping strategy for natural social interactions, we believe it still has potential if used with lower translation gain. We envision Scale being used for creating interesting gameplay involving super human capabilities. For example, if we were to replace the humanoid avatar with a flying wisp character, we think the fast unpredictable movements of the user in the smaller space, will become readily acceptable in the newer context, as they will be more in line with user expectations.

In summary, we found that two of the three mapping techniques provided a high sense of copresence and togetherness. Surprisingly, we found that the space mapping with the smallest shared space (Overlap) resulted in the least amount of proximity as it ended up being occupied mostly by the small space user. The different types of interactions afforded by the different mapping techniques suggest that experiences need to be specifically designed and matched with a mapping technique. They also suggest the audience for the designed experiences. For example, we may only want to create experiences for family members or friends when we know that the resulting personal space will be low. We summarize the findings relating to the design of mapping techniques in Table 6.

DESIGN GUIDELINES

We derived four guidelines from our experience of building and evaluating our system. We consider these guidelines useful for designing shared virtual experiences for remotely located participants, especially where each user has a different room-scale setup and is allowed to physically walk in VR. The guidelines focus on the structural elements of a shared virtual experience created by mapping different room-scale setups. Collaborative tasks, defined broadly, can be partly, completely, or not-at-all overlapping, and we have shown different mappings that support all these.

	Scale	Kernel	Overlap
shared space size	large	fair	small
personal space	high	fair	low
presence	high	high	high
social presence	low	high	high
togetherness	low	high	high
collisions	many	few	few
use of space	little	little	good
activity examples	travel games creativity	collaboration training education	sports healthcare tabletop

Table 6: Design implications for the three space mappings summarized.

Support Shared Space: To make the most of a room-scale setup, design experiences should allow participants to come together in the shared space when needed and explore individually at other times. This will support the most flexible use of each person's physical space while still supporting real-walking for locomotion and natural interaction in the shared virtual space. Depending on the type of experience (see Table 6) to be designed, the appropriate space mapping can be selected. For example, if the shared activity requires a lot of movement for each user, then Kernel is the best mapping technique. For example, remote collaboration for designing a large 3D object together where both need to freely move around the static objects or in education scenarios like viewing the structure of an enlarged molecule and viewing and manipulating it together.

Leverage Asymmetry: Instead of trying to fit all types of tasks into one type of shared virtual space, designers should leverage the inherent advantages of the different sizes of tracked spaces and the resulting mappings to design relevant tasks. For example, the Overlap technique is best suited for tasks where each user needs to maximize their movement space but the shared space can be small. Such a setup affords sports activities like ping-pong or tennis, or collaborative tasks where each user is placed on either end of a table, a room, or a hallway (meeting, tabletop games, or doctor/patient interactions in clinical psychology).

Design for Interaction: While all users are located in different physical spaces, they perceive the same virtual world. All users can hear and see each other doing things in VR, even if they are not directly involved with one another which can be distracting or engaging. Design tasks that require teamwork through shared manipulation of objects for creating challenging, productive and fun experiences.

Natural Embodiment: Our empirical work confirms that participants highly valued having an avatar that gave them the ability to ''physically'' and naturally engage with each other. Similarly physically walking in VR provided a satisfying sense of presence. We encourage creators of collaborate VREs to design shared spaces and interactions using natural locomotion, and only use teleportation or related transportation methods as a fallback technique if the space limit requires it.

Limitations and Future Work

This paper shows a first of its kind exploration of mapping techniques for remotely located multiuser VR systems. We decided on the three techniques because of their difference to cover a wide spectrum of applicative possibilities, given the physical space configurations supported by the HTC Vive. To entirely cover the gradient of social engagement, tasks and space mappings need to be modeled and studied as pairs. Our findings are based on two remotely located people taking a dance lesson together in a shared virtual environment.

In the future, we plan to extend our system to incorporate more simultaneous users to understand the limits of natural locomotion techniques and to explore combination navigation mechanisms. This will allow us to further investigate the novel design space of embodied remotely located VR experiences with natural locomotion and the impact of mapping techniques on social dynamics. Expanding the shared activity to include dances that require touching (e.g., waltz, tango) would benefit from exploration into haptics beyond vibrotactile feedback as included in the presented work. In such a scenario, the visual representation of solidity would be of special concern, such that when users interact, it should not appear as though their hands go through the other person's hands or body. It would be worthwhile to study mapping techniques for irregular space layouts as afforded by systems that use inside-out tracking similar to spaces created by [43].

We presented the design and user experience of three novel space mapping techniques together with their associated trade-offs in terms of phenomena like togetherness and use of space. Naturally, many more ways to blend physical spaces into multi-user virtual space are possible; we encourage further exploration in the area, that encompasses both algorithmic and user centric design challenges. Also, we encourage research in dynamic space mappings that may impact how space is mapped during immersion, based on, for example, users' activity and location.

CONCLUSION

In this paper we described the design, implementation, and evaluation of a VR system that allows geographically distributed embodied users to engage in a social dancing activity. We explored three ways of mapping two differently sized physical spaces to shared virtual spaces, and we report on how the mapping techniques influenced presence, social presence, togetherness, and movement. We found that the two mapping techniques, Kernel and Overlap, offered a high sense of copresence and togetherness, but caused different movement patterns, specifically when users were in close proximity. The mapping techniques support the design of different social activities based on movement and proximity requirements. A third mapping technique, Scale, showed reduced social presence and togetherness, but we foresee its usefulness in playful VR applications. We concluded with a set of design guidelines for creating social VR experiences for non co-located users.

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