Traces in Virtual Environments: A Framework and Exploration to Conceptualize the Design of Social Virtual Environments

Linda Hirsch, Ceenu George and Andreas Butz

Fig. 1. Traces of use in the physical and virtual environment: left) a natural trace of use from users in a physical environment [30], middle) traces of use example in the virtual and physical environment from our pre-study and right) the virtual living room scenario with traces of use explored in our main study. We included hands and a toddler to convey object sizes.

Abstract— Creating social Virtual Environments (VEs) is an ongoing challenge. Traces of prior human interactions, or traces of use, are used in Physical Environments (PEs) to create more meaningful relationships with the PE and the people within it. In this paper, we explore how the concept of traces of use can be transferred from PEs to VEs to increase known success factors for social VEs, such as increased social presence. First, we introduce a conceptualization and discussion (N = 4 expert interviews) of a "Traces in VEs" framework. Second, we evaluate the framework in two lab studies (N = 46 in total), exploring the effect of traces in (i) VE vs. PE, and (ii) on social presence. Our findings confirm that traces increase the feeling of social presence. However, their meaning may differ depending on the environment. Our framework offers a structured overview of relevant components and relationships that need to be considered when designing meaningful user experiences in VE using traces. Thus, our work is valuable for practitioners and researchers who systematically want to create social VEs.

Index Terms—traces, traces of use, asynchronous, social VE, framework, social presence

1 Introduction

In recent years, the interest in creating social virtual environments (VEs) has increased. This is evident in the growing amount of consumer platforms that are becoming available, such as AltSpace VEs [47], Mozilla Hubs [53] and the metaverse [46]. In parallel, research fields, such as learning [11, 52], work training [9, 27], and health [77, 78] are exploring how to create social VEs for long term use. Although these researchers are exploring social VEs in different contexts, they face the same challenge: The need to create meaningful relationships with people and places in VEs that users want to return to – for long-term rather than one-off usage. However, in the VE, spaces can be reset by the system or users to start on day zero. As such, VEs don't have the user-independent persistence that PEs have, making it more difficult to create meaningful user experiences and user-VE relationships.

In physical environments (PEs), the concept of traces of prior human interactions, or traces of use, can be used to create meaningful relationships between people and PEs, and people and interfaces [1, 61]. For example, a trodden path in the grass shows where users walk outside of pre-designed walkways (see Fig. 1), or worn-out seating areas in an environment show a history of user interactions and behavior patterns in context. Thus, traces signal the repeated usage of social environments and can turn an artificially defined space into a social, vivid place [1, 14].

In this paper, we explore whether traces of use can be systematically transferred from PE to VE to leverage their benefits for social VEs. Additionally, we aim to understand whether known success factors such as social presence can be improved by designing with traces of use.

Multiple design guidelines for social VE applications document the need to focus on changes in the environment. Schultz et al. [45] highlight the need to personalize the place and architecture of VEs, as one of their design considerations. Jonas et al. [37] identify "User Manipulation of the environment" as a design dimension in their "Taxonomy of Social VR Design". Although they include user-made changes in the environment as an influencing factor for successful social environments, it is unclear how to apply traces of use for VEs systematically. Our work closes this gap by conceptualizing research on traces of use for VEs guided by the research question:

RQ How can the traces of use concept be leveraged to conceptualize the design of and research on social VEs?

To address this question, we propose a conceptualization of research on traces of use, which was refined in (N = 4) expert interviews. As a result of these efforts, we introduce a "Traces in VEs" framework, including all established dimensions and relationships to be considered when designing with traces. We purposefully differentiate "Traces in VEs" from traces of use to indicate it as a design concept to create meaningful and social VEs, in which selected traces of use are applied a) to support a certain (i.e., social) atmosphere and b) serve as indicators for activities and interactions, which are not necessarily related to worn-off material qualities [63] such as visualized common gaze points [60].

- *Linda Hirsch is at LMU Munich. E-mail: linda.hirsch@ifi.lmu.de.*
- *Ceenu George is at University of Augsburg. E-mail: ceenu.george@ifi.lmu.de.*
- *Andreas Butz is at LMU Munich. E-mail: butz@ifi.lmu.de.*

Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org. Digital Object Identifier: xx.xxxx/TVCG.201x.xxxxxxx

To evaluate the framework in practice and to explore the traces' effects in social VEs, we also present the results of two lab studies: The first, between-subject pre-study (n = 20) targeted the comparison between the perception and interpretation of PE versus VE traces by replicating a PE in a VE and letting each user experience one of these environments. In the second, within-subject study (n = 26), we explored the traces' effect on social presence by comparing users' experiences in a room with and without traces. We focused on social presence because it is an essential success factor for a meaningful and immersive user experience in social VEs [3]. However, there is little research on approaches for fostering social presence in long-term VEs.

Both studies revealed that the perception and interpretation of traces in PE are similar to VE, which suggests exploiting PE research knowledge for the design of VEs. The main study additionally confirmed the traces' positive effect on social presence and the feeling of connectedness. To our knowledge, our work is the first structured exploration of traces of use and their applicability in VE to increase social presence. Consequently, we see our work as a first step to introduce the traces in VEs concept to the community to support a systematic approach for creating social environments and meaningful user experiences.

2 Related Work

Below, we will provide an overview of a) the traces of use design concept for PEs, b) design concepts similar to the traces in VEs, and c) research about virtual social presence.

2.1 Designing with Traces in PE

The foundation of the traces design concept originates from materials experience design research, where the material embodies the interactions and experiences through material changes, namely traces of use [23, 24]. Besides, research in augmented environments and interfaces applies the concept to indicate movement patterns [1, 51], reveal touch behaviors [31, 62] and enable collaboration and shared understanding [12], in order to increase social connectedness and awareness [1, 12, 33]. Additionally, traces of use are defined depending on the user's prior habits or expectations towards, e.g., the position of an object or an object's settings such as the adapted height of a table [5, 17]. Depending on how and in what context a trace had been created, it can also convey a deeper personal and emotional meaning, revealing a strong and personal user-object relationship [74, 75]. E.g., a mug's notch might remind its owners of amazing travel times, turning it into a unique and personal object for its owner [41, 63]. In PE, designing with traces of use frames the socio-ecological context of an interface. It includes designing with the dimensions time, material changes, and the relations between people, environment, and materials [61]. The design concept supports the communication of memories and experiences of a place [2, 13], of objects or materials [23, 75] and people [12]. Additionally, the traces are also perceptible evidence of time and transience applied to trigger user reflection and draw connections to prior knowledge and cultural customs [12, 50]. Evidently, users' interpretation and perception of traces are context-dependent and influenced by the place, time, interaction, the users' background, and the material or object embodying the trace. Robbins [61] introduced a framework positioning traces as the central factor to communicate and represent the meaningful connections between people, materials, and practices. Yet, there is no framework reflecting their role in spatial design that could be used to apply the concept in VEs.

2.2 Trace-Like Design Concepts in VEs

"Leverage the known world to shape behavioral expectations and cue familiar social contexts through the aesthetics of place and architecture" is one of the design considerations that Schultz et al. [45] propose to design social VEs. Although they do not explicitly mention traces, they also propose to create meaningful relationships with the environment by personalizing them based on prior experiences (in PEs). In their *Taxonomy of Social VR Design*, Jonas et al. [37] further stated that changes in the social environment or the VE, made by users, are necessary for long-lasting relationships with social places.

Game VEs embed spatial design features similar to traces of use by using, e.g., visual markers to support navigation [21, 38] or to increase players' social awareness [29, 34]. However, these markers do not represent the actual number of users who navigated through this environment but are static, non-evolving designs. Such visualizations are not related to any prior user interactions but system-generated features integrated to evoke a similar effect as real traces of use. Horizon Zero Dawn [21], e.g., integrates them in the VE by default to guide players to move in a certain direction. Another "traces"-like design feature derives from a player's actual interaction with the game: In World of Warcraft [18], players leave marks in the environment to asynchronously communicate to, e.g., coordinate the order of an attack. Similarly, in No Man's Sky [29], players can leave behind messages for other players. These examples are related to the PE traces concept. Yet, they still differ by being purposefully placed and direct communication cues instead of implicit and dynamically evolving traces that change shape and characteristics according to the user's attributes (i.e., left hand vs. right-hand imprint). These examples are not exhaustive. Nonetheless, they show a clear difference between our concept of traces of use and existing, trace-like game design features.

2.3 Social Presence in VEs

Social presence is a measurable indicator for users' sensation of others within a shared VE [58]. Optimizing for social presence is valuable, as it has been identified to positively affect immersion [66, 79] and satisfaction [28]. The majority of prior work on social presence was completed in co-located, synchronous settings, where at least two users are in the same VE [3, 40]. An increase in social presence was found, for example, when bio-feedback was shared synchronously [36], co-located avatars [22, 65, 68] mimicked users' facial expressions [70] using verbal and non-verbal cues [19, 28, 35, 64] and co-located users were in close proximity [54].

In comparison, there is little work on asynchronous interactions and social presence, although such settings are gaining popularity among VE users. In an asynchronous online teaching environment, the students who had created relationships with their fellow students felt a higher social presence than those who had not [66]. Social presence has been confirmed to positively correlate with user engagement [79] and satisfaction in VEs [28] and negatively with mental effort [73]. In another example, researchers focused on asynchronous remote collaboration considering prototype developments [9, 56]. In these scenarios, collaborating teams purposefully altered aspects of and within the environment in agreement, e.g., replacing virtual objects [9].

2.4 Summary

Overall, when aiming for a meaningful user-VE relationship, users should be able to alter and personalize the VE. Social presence is an established measurement to evaluate a VE's social factor. From a design perspective, this means establishing a visual language that enables shared understanding and communication [6] and allowing persisting environmental cues so that users can draw connections to their prior experiences and follow up on others' activities within the VE [71, 72]. We hypothesize that traces can support these processes and increase social connectedness in VEs through spatial design. Because there are currently no tools that would support the design process of traces in VEs, we conceptualized a framework (see Fig. 2) that we refined in four experts interviews. It is based on the traces framework by [61], where the material dimension also includes objects and their characteristics. We will explain the framework and its refinement process in the next section.

3 The "Traces in VEs" Framework

Our work introduces the "Traces in VEs" framework to conceptualize research on the design of social VEs and to support designers in their process when designing with traces in VEs. It provides a structured overview of established dimensions and relationships that traces of use can influence or are influenced by. Consequently, it explains the interdependencies that can increase or weaken the traces effect of creating meaningful VEs.

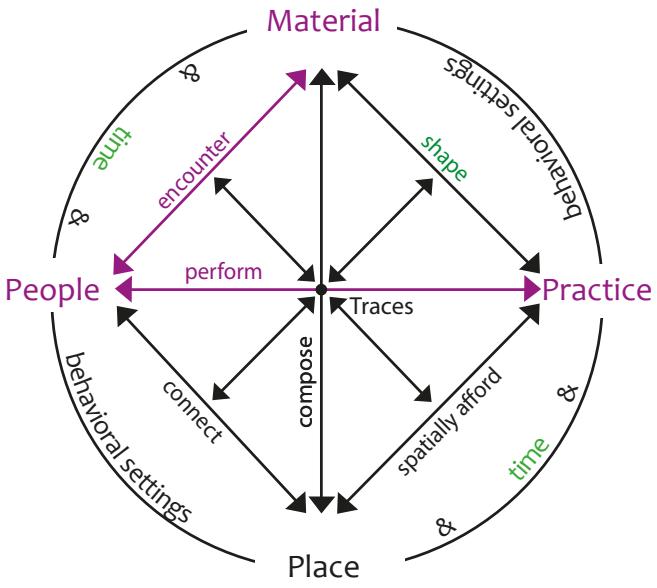

Fig. 2. "Traces in VEs" framework with dimensions & relationships that need to be considered when designing social VEs. We indicate changes based on the expert validation in green and emphasize the relations to the materials experience framework in purple.

3.1 Rationale and Development Process

The initial version of the framework was an adaptation of the materials experience framework [23, 61]. The framework defines traces as evidences of prior experiences and thus, meaningful features in an interface. Additionally, they are also environmental characteristics and evidence of social encounters that turn any environment into a meaningful place [14]. We, thus, extended the framework by Robbins et al. [61] with the dimensions *Place*, *Time* and *Behavioral Settings*. We consider these changes essential to apply the traces design concept for the spatial design of VEs because the original framework focuses solely on the user-material-practice relationship without discussing the role of environments in this context. Additionally, behavioral settings have not been explicitly considered in prior frameworks. Still, they are integrated into the cultural and personal background of a user that essentially influences the interpretation of PE traces [2, 32]. In addition to these iterations of the framework, we adapted it further after (N=4) initial expert interviews, which are described at the end of this section. The resulting changes are twofold: (i) We renamed the material-practice relationship from collaboration to shape, and (ii) we added time as a more prominent, independent dimension. These post-interview changes are indicated in Fig. 2 in green, marked as (**PI**) and described in detail throughout the next section where appropriate.

3.2 Framework Dimensions and Relationships

In our framework, the traces serve as evidences and connection points of the intersecting relationships between the dimensions *People*, *Material*, *Practice* and *Place*. At the same time, they are influenced by and changed through the individual and the interplay of the dimensions. Thus, they are ever-evolving entities. The temporal development is recorded in the *Time* dimension on the outer circle (**PI**). Together with the *Behavioral Settings*, these dimensions correspond to persisting influences on user experiences, on which the designer has an only minor influence. In contrast, all other dimensions should be considered in the design decisions, such as deciding who to design for, material or object choices. As changes within one dimension affect the perception of traces and the other dimensions, the relationships are bi-directional.

Dimensions: The *People* dimension comprises direct and indirect users, virtual user representations, such as avatars, as well as system personifications. People may be one or many persons. The dimension describes the personas and target groups for which a VE is designed. This includes potential bystanders that may be affected by interaction or share the same VE and other social entities (e.g., animals) directly or indirectly connected to an interaction. Selected *Material* choices and characteristics, such as perceived shape deformation and texture differences, influence users' sense of place and overall presence in a VE [42]. The dimension comprises objects that consist of a multitude of materials. In contrast to PE, where haptic feedback is also prominent, VE experiences are still mainly vision-based. Accordingly, visual material and object characteristics [62] are prominent features in this dimension and VE experiences. *Practice* corresponds to "ways of doing" [23] in the form of daily practices and routines. This dimension includes traces caused through one-time (e.g., the damaged mug example) and accumulated (e.g., the trodden path example) interaction and intangible interactions, such as eye gazes. The concept or sense of *Place* contributes to the level of user immersion and reflects a VE's narrative and ability to communicate this narrative [39, 55]. We purposefully introduce *Place* instead of environment because places, in comparison, are characterized by meaningful social encounters [14] that embody and communicate their users' experiences and prior happenings. In contrast, a person's cultural and personal background informs their *Behavioral Settings*, and thus, their behavior in and interpretation of the VE. *Time* reflects the continuous temporal development of a VE. This includes synchronous and asynchronous processes, as well as momentary situations.

Relationships: Based on the materials experience framework [23], people's initial *encounter* with materials shapes their expectations and judgments. Similarly, people *perform* conscious or unconscious practices in and may build a *connection* to a VE. At the same time, places as shared, social places can connect people. They further *compose* materials and *spatially afford* certain practices [45]. In turn, practices can change a place's spatial affordance and dynamically shape materials by changing their characteristics over time. Yet, materials can also shape and define practices. We exchanged the term *collaborate* describing the material-practice relationship in [23], into *shape* (**PI**). This change was necessary, as the experts did not understand the meaning of the original term and *shape* was the most popular one each of them brought up individually, as a description of the bi-directional relationship (**PI**).

3.3 Expert Interviews

We conducted four semi-structured interviews with experts (self-identified male = 2, female = 2, age:M = 44/SD = 14 years, experience: M = 6.25/SD = 1.26 years) from four different institutions to validate the framework and to discuss its potential in VE. The interviews were conducted in the experts' mother tongue and citations were translated into English. All anonymized transcripts can be found on osf.io[1]. We recruited participants through the department's research network.

3.3.1 Interview Process & Analysis

Expert interviews are known to be most efficient in initial and exploratory research phases [7]. We aimed to identify similar concepts in ongoing projects, relevant dimensions and relationships when designing with traces, and the concept's design potential in VEs compared to PEs. Furthermore, we discussed our "Traces in VEs" framework with them for validation (see the validated version in Fig. 2). Each session included an introduction to the traces of use concept and framework. We interviewed the experts via zoom and recorded sessions with their consent. Recordings were stored and processed according to GDPR. The interviews, on average, took 44 min (SD = 20.1 min). They were transcribed using GoTranscript [43] and subsequently, independently thematically coded by two researchers using condens.io [25] and miro [49]. We mixed the deductive approach [59] based on the questions asked (regarding traces and the framework) to define the main themes; with the inductive approach [8] for any sub-themes. The

[1]We provide the transcripts in the experts' mother tongue and study questionnaires on `https://osf.io/xj72k/?view_only=b421002857f943dfb02424390e3031b`.

interviews resulted in 89 unique codes before consolidation and an inter-rater agreement [20] of 88%. The coding disagreements were due to missed aspects in the interviews and misunderstood code terminology. After alignment in the second iteration, our coding scheme comprised 64 unique codes for two main themes (framework and traces), with eight and five sub-sub-themes each. We provide the complete coding scheme in the supplementary material. In the next section, we present the results divided into the two main themes *Traces* and *Framework*. Each main theme also resulted in sub-themes, which are underlined and discussed below.

3.3.2 Results & Discussion: TRACES

Type: The first sub-theme, the trace *type*, includes the traces' nature and making such as whether they were created by a one-time incident or through accumulated interaction. Similarly, the nature of a trace differs in appearance from very natural-looking with irregular shapes to an abstract, clear shape appearance. However, naturally appearing traces can also be artificially created by a system or a human. Additionally, experts classified digital traces as ephemeral ones that are harder to preserve than physical ones. However, expert three also told us about their research project of exploring a similar time concept of showing movement patterns of prior users in VEs by either showing *"one [visualization] that remains [and] that you can see where someone has walked [...]. And one, that kind of stops after a while, and disappears"*. Furthermore, the same expert compared intentionally and unconsciously caused traces by differentiating between purposefully implemented and positioned traces and those that appear more as a by-product. Lastly, experts mentioned a variety of single and multi-modal traces, such as thermal or acoustic traces, that could be explored in VE. Expert four added the need to provide a clear *"interaction-perception loop"* to users that allows mapping their interaction to the system reaction cognitively.

Characteristics of Traces: This sub-theme comprises another three sub-sub-themes, namely *Common and Transferable*, *VE-Specific Measurements* and *VE-Specific Traces and Characteristics*. *Common and Transferable* trace characteristics emphasize persistent trace qualities independent from reality, e.g., emphasizing the affordance of an interface or an environment. By linking the topic to VE games, expert one gave the example of traces applied to nudge people to move their game figures in certain directions. In general, traces stand out through unobtrusive, attention-inviting characteristics that reveal additional information and support intuitive interaction. Expert two, for example, imagined applying traces to augment an environment and indicate where the majority of environment users had been standing before to understand the spatial usage and points of interest intuitively. *VE-Specific Traces and Characteristics* also provide the opportunity to personalize such information: *"In VEs, we of course, have the opportunity to pre-select things, to highlight things. Bringing the relevant information to the foreground.", expert four*. Experts also emphasized that by nature, VEs, in comparison to PEs, do not normally contain any traces. Thus, every trace in VEs requires a conceptual model that aligns with the user's mental model to achieve the effect intended by the designer. This introduces additional challenges of trust and user's learning ability. To refer to expert one: *"You can't trust it that much, that's why: yes, there are traces, but not really, because they aren't really traces"*. In contrast, the user's learning ability needs to be researched: How quickly and easily do they understand the intended message behind a trace? It further requires *VE-Specific Measurements* such as gaze and attention sharing.

Limitations and Challenges: Linked to the traces' characteristics, experts pointed out limitations and challenges when applying traces in VEs, such as their scalability and the currently still limited technical feasibility. Traces are also very complex, multi-dimensional artifacts because they consist of various variables (e.g., color, shape, size, depth, etc.), which are challenging to balance and implement. Additionally, traces can also be exclusive, particularly when digital traces are either only presented to certain user groups or collected from user interactions that the user is unaware of. The latter point also requires ethical considerations and setting up a certain code of conduct when designing with traces.

Effect: This sub-theme combines the effect of traces on users and the designer's goals of implementing them. Experts found traces to increase the level of reality in VEs, enable asynchronous communication between users and be useful for analysis purposes to visualize individual and mass user behavior. Traces as evidence of prior interactions could also become a shared social focus leading to people replicating the same movement or interaction that led to the trace creation: *"From a user perspective, I think it's a really great way to create such a social feeling that you see someone else was here and someone else draws your attention to [something or somewhere]", expert two*. The traces can also embody meaningful relationships between users or the user and the VE through such associations. However, the effect of traces in a VE compared to a PE might be entirely different considering a user's inhibition of leaving traces or intensifying existing ones.

Design Requirements: Experts also saw design requirements, such as adapting the traces for specific groups or considering their context-dependent change of meaning. This links to whether users can identify if a trace is system- or human-created and rewards them with a certain level of autonomy toward developing a scenario. The effect should further be measurable and communicated to users to keep them in control of the tracked, personal data, and interactions.

3.3.3 Results & Discussion: FRAMEWORK

All experts confirmed the importance of each dimension and their relationship among each other and the potential of the traces to serve as evidence of the relationships.

Dimension: We split this sub-theme into two more sub-themes considering the experts' feedback on existing and suggested additional dimensions. Experts emphasized the importance of the user-place relationship and the meaningful relationships between the dimensions in general for the existing dimensions. Each dimension represents a perspective that designers can use to evaluate their concepts. Considering VEs, they were unsure about the role of virtual agents and how to integrate them into the framework. For now, all four could imagine to add them to the people dimension, depending on whether the agent represents an actual human user or a system avatar and to iterate on the framework once the traces in VEs concepts is further established (*"Maybe in a next step, when you are more clear about what role real people actually play", expert three*). In contrast, all agreed on time as an important influencing factor that should be reflected in the framework from the start (**PI**). Additionally, they wondered about each dimension's level of autonomy and how to define it.

Usage: Experts found the framework descriptive and a useful design tool to communicate with other project members and assure that all relevant dimensions were considered. At the same time, each project would have a different focus, requiring the framework to be adaptable to the respective context and allow for a certain degree of freedom. For example, expert one mentioned that not all relationships and dimensions are always relevant, so that they would ignore the non-relevant ones for the time of the project. In contrast, the framework could support exploring the VE design potential by using the trace dimension to explore VE-specific qualities and how they might influence the user-object relationship. Expert two mentioned the example of children that could *"daub walls or something like that, which might be a nice experience for them and might even strengthen the connection to the object, [and] which you might not want to have in the real world"*.

Extension Potential: We grouped all codes about potential, "nice-to-have" changes in this sub-theme. One suggestion was, for example, to multiply the framework to reflect the potentially split user attention between PE and VE. Another question arose around naming the "people" dimension and whether "user" would be more suitable. However, we leave these points for discussion and future work without considering them in the framework.

3.3.4 Summary of Interview Results

Our experts confirmed that designing with traces in VEs has similar potential to their PE application to, e.g., communicate spatial affordance [2, 30] and to strengthen the feeling of social presence and connectedness [1, 12] (see **H2** below). However, VEs increase the complexity because every trace has to be purposefully implemented and designed, in contrast to traces in PEs (see **H1** below). This raises the questions of how to indicate whether traces are human-made or system-made and how to balance the implementation effort with the intended effect. Additionally, experts imagined the framework as a useful tool in the design process by facilitating communication within a team and to ensure that all relevant design dimensions were considered. Based on these interview results, we formed the following two hypotheses to evaluate the traces of use concept in practice and understand the effect of traces further:

H1 Traces of use are interpreted and perceived similarly in VEs and PEs.

H2 Designing VEs with traces of use increases users' social presence.

We conducted two lab studies to explore these hypotheses, which we describe in the next section before discussing the framework itself in the light of the study results.

4 Empirical Lab Studies

To explore the traces' effect in VEs, we conducted two studies: First, we conducted a between-subjects pre-study (n=20) to evaluate the transferability of traces by looking into the perception and interpretation of differences between PE vs VE. This was followed by a within-subject lab study (n = 26), investigating the effect of traces on social presence in VEs. Both studies received ethical approval from the ethics board of [kept empty for anonymity].

4.1 Setup & Study Procedure

Both studies shared the same technical setup of VEs and the same means of data collection and processing. Before entering the main task, we also introduced all participants experiencing a VE to a training environment, where they were asked to complete a small script including four tasks (turn left and right, pick up an object, move around with the object, and place it in a pre-defined spot). For integrating the traces, we designed them based on Baxter et al. [5]'s definitions and considered our framework to create a social VE where the integrated traces make sense to the users. The four types of traces of use that we considered in our design were: a) object characteristics, b) object state, c) object setting, and d) object context. Object characteristics are non-reversible, like a cracked mug. The object state describes reversible conditions, such as a crumpled pillow. Object settings describe (user-specific) configurations, and the object context includes changes to the object's location or surroundings.

4.1.1 Technical Setup

We developed the VE scenes in Unity version 2020.2.7fl and prepared individual objects, such as the pillows, in Blender version 2.91.2 or used objects from the asset store. Users experienced the scenes through an Oculus Quest [57] HMD.

4.1.2 Data Collection, Processing and Evaluation

In the main study, gaze behavior was logged directly to a file in the VE platform and analyzed to calculate the number and duration of views at each relevant object. All questionnaire data was collected and stored via limesurvey [26]. The researchers' institution holds licenses assuring safe and secure local data storage according to GDPR, about which all participants were informed and gave their consent. Before evaluation, we anonymized all data sets by storing and processing them under user IDs only. In addition, all citations were translated from the users' mother tongue to English by the authors. We evaluated the data using descriptive statistics and coded the answers to open-ended questions applying inductive thematic analysis [8]. The quantitative data was evaluated in R version 3.6.2.

4.1.3 Participant Recruitment during the Pandemic

We recruited all participants via personal networks to adhere to local Corona restrictions and decrease personal contact. We conducted the pre-study at a private residence and the main study in participants' homes.

4.2 Pre-Study - Effect of Environment on Perception and Interpretation of Traces

The pre-study (n = 20) focused on assessing qualitative data by interviewing users about their interpretation of the traces and their effect on users' perception of the environment. We conducted the study in a private backyard used as a shared place for residents in this PE and replicated the same place in a VE. 20 participants took part in the pre-study, 11 self-identified as female, nine as male (M = 33 years old; SD = 17). Ten participants had no prior experience in VEs, seven had had one prior experience and three more than one prior VR experience. The study was guided by the following hypothesis:

H1 Traces of use are interpreted and perceived similarly in VEs and PEs.

4.2.1 Traces of Use and Questions

Within the respective environment, we integrated six objects with traces of use (see Fig. 3): a *characteristic* trace in the form of an irreversibly broken glass bottle, a scratched wood surface of a bench as a reversible *state* trace, a deckchair set to a certain upright position as *setting* trace, and paper balls next to a trash can to visualize *contextual* traces. Additionally, we added a picnic blanket with two overturned and six other toys and earth on a chair and the floor from a plant pot positioned next to it. We asked users to interpret the story behind each of these traces in a post-survey, such as who caused it and through what interaction. Additionally, users rated how negatively or positively they perceived each trace on a 5-point Likert scale (1=strongly negative to 5=strongly positive).

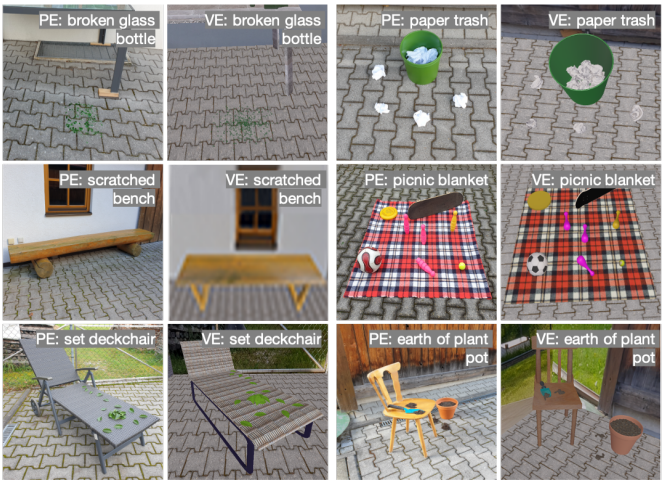

Fig. 3. Traces in PE vs. VE in comparison.

4.2.2 Procedure

We introduced participants to the study and collected their consent. Afterward, participants exploring the VE experienced the training environment. Otherwise, we randomly assigned them to either VE or PE environment for the main task given the following scenario to read: "You arrive in the back garden of one of your friends. They told you to wait there, as they are running late. As you have never seen this part of their house, you curiously explore the back garden". Then, they were encouraged to move freely and return to the starting point. Subsequently, participants were asked to complete the post-study survey.

4.2.3 Results & Discussion

PE participants perceived the traces' effect on the environment as normal (4/10), interesting or appealing (4), and either real (1) or surreal (1). In comparison, eight of ten VE participants found traces to make the VE more realistic and natural. From the remaining two, one person emphasized the importance of considering the traces' detail and fineness, which allowed to draw connections between the trace and their creators and the environment. Similarly, the last person was reminded of a dream journey when seeing the traces.

To evaluate **H1**, we compared the overall rating of traces per environment. We tested the data for normal distribution with the Shapiro-Wilk normality test followed by an independent t-test. The t-test showed statistically non-significant results (t = -0.195, p = 0.846) and a small effect size (Hedges' g = -0.036). Following the results up with the Bayesian independent sample t-test, it indicated that it was about five times as likely that there was no significant difference, BF_{01} = 4.998 between the perception of VE and PE traces[2].

Regarding the associated making of the traces, all but two participants from both environments agreed on the bench's traces being caused by either a patina effect accumulated over a long time and usage or a weathering effect from external forces (i.e., wind, rain). The remaining two did not notice the traces on the bench. In general, participants linked the majority of traces to prior human interaction and associated certain behaviors in both environments. As such, the picnic blanket was associated by six PE and five VE participants to children playing in the backyard, which would trigger *"[...] positive emotions because children, maybe together with parents, play together.", VE10*. Similarly, the associated activities made participants reflect on the causer's behavior. In the case of the paper trash can (15/20), the earth (12), or the broken glass (18), participants interpreted careless behavior that would additionally litter the environment and provide potential harm (*"[...] and someone could get hurt through the broken glass.", VE8* or *"risk of injury to children", PE5*) for other place users. Additionally, our design intention of testing the traces as evidence of prior human interaction succeeded 111 times (20 participants * six traces - 9 unrecognized traces). Participants related the traces to natural, external influences only in the case of the bench and the deckchair.

4.2.4 Summary

Altogether, our exploratory pre-study shows the tendency that traces are similarly perceived in PEs and VEs. This means that known characteristics from PEs (i.e., [32, 61, 63]), such as the patina effect or breakage, can be transferred to VEs. The traces made the VE appear more realistic and natural and gave participants the impression of prior human activities that allowed assumptions about other users' behavior and character in most cases. Thus, the traces supported participants' understanding and sense-making of what happened within the environments, indicating an increased awareness of asynchronous social presence. However, we also saw the need to reduce the traces' ambiguity by designing them even clearer as being related to human interaction and not from external physical forces (or a system).

4.3 Main Study - Effect of Traces in VEs

In the subsequent main, within-subject study (n = 26), we compared a virtual living room in two versions: one with traces and one without traces (see the one with traces in Fig. 1). Participants were on average M = 41 years old (SD = 16.9), 15 self-identified as female, 11 as male. 13 had no prior experience in VEs, seven had had once an experience, and six had had more than one experience. We purposely chose an indoor scenario for the main study to counterfeit the back-garden ambiguity, which some participants in the pre-study perceived. The living room scenario may be perceived as a personal yet shared place where traces of personality are natural and expected depending on the context (e.g., private household versus staged interior design). Based on the results of our expert interviews, we complement the qualitative measures of the traces' effects with a quantitative exploration of social and spatial presence. Thus, this study is guided by the following hypothesis:

H2 Designing VEs with traces of use, increases users' social presence.

4.3.1 Independent Variables

We considered the traces of use embedded into the virtual living room our primary independent variable with two levels: with and without traces. To evaluate the recognizability and effect of the traces, we introduced the type of trace [T_n] of use [5] as the second independent variable (see Table 1). We included at least two examples of each trace type on a total of 13 objects.

4.3.2 Dependent Variables

We tracked participants' viewing time and behavior per room, their feeling of social presence, and general presence as dependent variables. We implemented an invisible cone (radius = 0.5m, height = 5.3m) that followed users' eye gaze to track the viewing behavior, which was inferred from the head tracking data. Considering the size of the VE (4.8, 4.8, 2.5m), the cone was able to track all objects equally, independent of user position. Intersecting this cone with the scene allowed us to track the number and duration of views users looked at individual objects in real-time. A view at an object was only registered after a dwell time of at least 0.1 seconds, considering the defined eye fixation time by Dupont et al. [16]. We used five questions from Bailenson et al.'s [4] questionnaire for interpersonal distance in immersive VEs to measure the social presence. As the questionnaire was originally developed for asynchronous social cues, we adapted the questions to accommodate our study context and goal. E.g.,"I perceive that I am in the presence of another person in the room with me." was turned into "Do you have the perception that others have used the room before you?". We kept the original rating scale (-3 ="I totally disagree"; 3 ="I totally agree"). We also added questions about users' feelings and connectedness to other room users, e.g., "It is easy for me to understand how other users felt while being in the room", using a 5-point Likert scale (1="I totally disagree"; 5="I totally agree"). Lastly, we measured the general presence using Slater et al.'s [69] questionnaire, asking about users' demographics, their prior VE or interactive digital 3D experiences, and open-ended questions about their room experiences.

Table 1. Traces of use types in the VE: We integrated at least two objects for each type of trace [T_n], and added combinations of traces by changing the respective object's context and the state to enrich the environment further and emphasize differences.

Traces of Use Type	**Object**
[T_1] Characteristics	Colored paper and gas-filled balloon
[T_2] State	Crumpled pillows and opened markers
[T_3] Settings	Open magazine and turned chair
[T_4] Context	Position of the football and small teddy
[T_5] Combinations	Rearranged and altered chessboard, puzzle, books, vinyls, and an big teddy.

4.3.3 Procedure and Tasks

Every participant gave their consent and filled out the pre-questionnaire. They then entered the training environment before receiving a background story to the living room scenario. We applied Clarke et al. [10]'s story completion method in order to capture participants' mental model. Participants were asked to imagine that they were Alex, a student who uses the VE to connect to other people in times of increasing remote work and study. Alex doesn't know the other room users yet but knows they share common interests. With this introduction, participants experienced the first virtual living room by looking around and making assumptions about whom they shared the VE and telling us what traces led them to their assumption. Participants had as much time as they wanted. When participants indicated to be done exploring, we asked them about their social presence and emotional connectedness to the imaginary other users. We noted their verbal responses while they were

[2]We used the default prior of Cauchy = 0.707. We also tested other prior factors by varying them from 0.507 to 0.907 in steps of 0.1. We could not identify substantial differences.

in the VE to capture the immediate impression and effect of the respective environment. Participants were then introduced to the second room, following the same procedure as before. The room order was counter-balanced with 50% entering the room with traces first, followed by the room without traces and vice versa. After experiencing both virtual rooms, participants completed a post-questionnaire comparing them and their general feeling of presence.

4.3.4 Results

Our data revealed significant differences when comparing the room with vs. without traces with a Wilcoxon signed-rank test ($p<0.001$). Before, we tested the data for normal distribution with the Shapiro-Wilk normality test.

Table 2. Head-tracking results: Participants looked significantly more often and longer at the different objects in the VE with traces (p¡0.001).

Room	*M* Views	*SD*	*M* Duration (sec)	*SD*
With	9.2	3.7	17.67	12.8
Without	5.7	3.1	7.58	4

Tracked Times and Objects: The head-tracking data showed that participants looked more often and longer at objects in the room with traces of use. Comparing the total numbers of looks (see Fig. 4 and Table 2), the Wilcoxon-Signed-Rank-Test showed a significant difference (W=132, p <.01) between rooms. Similarly, the average duration of looking at the objects was significantly longer for the room with traces (W=140.5, p <0.001). On average, participants looked 10.1 seconds longer at the objects in the room with traces while also staying about 30 sec. longer (with traces: M = 321.2 sec., SD = 120.1 sec.; without traces: M = 291.1 sec., SD = 75.2 sec.).

We did not find any significant difference in the individual type of trace [T_n], thus, we report descriptive statistics for each room. Room with traces: Participants looked longest at the crumpled [T_2] pillows (M = 52.9 sec.) but also with a high deviation of SD=49 sec. The least considered object was the [T_1] balloon (M = 1.9 sec., SD = 7 sec.) in the same room. The highest average count of views was at the [T_5] books (M = 16, SD = 14), and the lowest at the [T_1] balloon (M = 2, SD = 7).

Room without traces: Participants looked longest at the [T_5] big teddy bear (M = 12.6 sec., SD = 18 sec.) and shortest at the [T_5] books, (M = 2.9 sec., SD = 4 sec.), and most often at the [T_4] game of chess (M = 13, SD = 15) and least at the [T_5] vinyls (M = 2, SD = 3) and [T_5] books (M = 2, SD = 2).

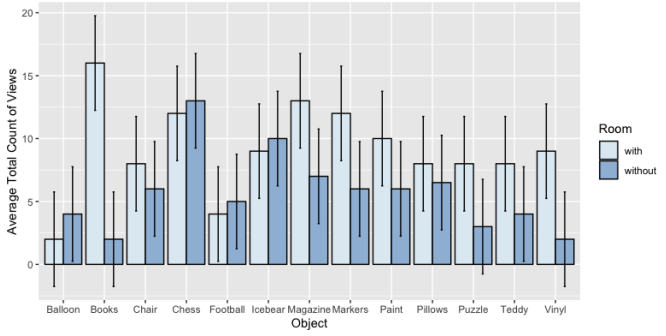

Fig. 4. The average total count of views for each object.

Social Presence and Feeling of Connectedness: We applied the Wilcoxon-Signed Rank test showing that the room with traces of use triggered a significantly higher feeling of social presence than the one without (W = 502, p <.01). The data was not normally distributed. Participants scored the room with traces M = 3.23, SD = 3.71. In contrast, the room without traces was scored M = -1.46, SD = 5.59. Fig. 5 shows the difference. Spearman's rank correlation was computed to assess the relationship between total time spent in each condition (with vs. without traces) and social presence. We could not confirm a correlation between the two variables, r(24) = -0.09, p = 0.6. vs r(24) = -0.12, p = 0.5. Thus, indicating that time spent had no effect on social presence results. We evaluated the questions about users' feeling of

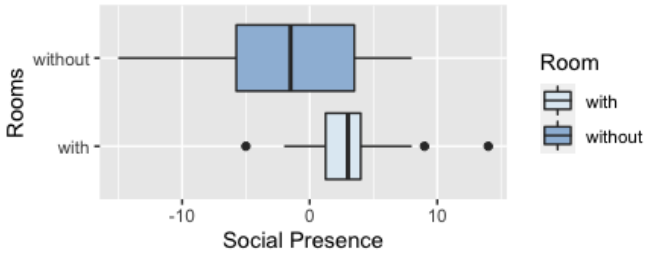

Fig. 5. Social Presence Ratings: Participants felt a significantly higher social presence in the room with traces of use.

connectedness individually using the Wilcoxon-Signed-Rank-Test. We found the only significant difference was that participants felt it was easier to understand how others felt in the room with traces of use (W = 467, p <.05). Overall, participants felt moderately present in our VEs (M = 4.06 on a scale of 1 to 7; SD = 0.68).

Qualitative Feedback: Participants stated what they liked or disliked about the rooms and revealed diverse opinions. Twelve liked the room with traces of use for being "homely", "inviting", "vivid", and "authentic". It would make them *"[...] feel like a person here. It is natural not to clean up everything and leave something lying around. You do not return a room to its original state when you leave it.", P26*. The room without traces left a sterile-looking impression, instead, e.g., *"It doesn't look homely at all but reminds you of a doctor's waiting room.", P11*. In contrast, however, six people preferred the room without traces of use because of its clean, well-structured, and tidy characteristics. In comparison, these six people felt rather disturbed by the traces of use: *"Something was going on in the room, and I don't know who was here or what exactly happened. That unsettles me a little.", P17* or reminded of real-world duties: *"One would have to clean up here. This is what my child leaves behind, and then I have to clean up afterward", P21*. Eight participants did not indicate a clear preference as they either liked the room design overall (1/8), saw advantages in both rooms (4/8), or felt neutral about either (3/8).

5 Discussion

In this section, we resume discussing the framework (**RQ**), followed by reflecting on the traces' potential and characteristics in comparison between PE and VE (**H1**), and the traces' meaning in the design of social VEs (**H2**).

5.1 Discussion of the "Traces in VEs" Framework

5.1.1 Validation of the Framework

We see the "Traces in VEs" framework as a tool that supports designers and practitioners to create VEs – system models – that match the users' mental models. Furthermore, it provides a systematic overview of relevant design dimensions for developing meaningful and social VEs. For example, the virtual living room was designed to represent a personal and social gathering place for people sharing the same virtual "household". This setup, in combination with the integrated traces, such as the colored paper, made participants associate specific interactions and activities within the VE that had previously happened, i.e., *"This is what my child leaves behind [...]",P21*. We created a VE that users could relate to by considering our framework's dimensions and relationships and thus, provided the basis for a meaningful user-place relationship [45].

In both our studies, participants interpreted the traces in relation to the framework dimensions combining the contextual information (i.e., the shared living room) with their personal background (behavioral

settings; i.e., "clean up after my children") – supporting **H1**. For example, VE7 interpreted the earth next to the plant pot in the pre-study as *"Gardening was probably being done here by one of the adult residents of the house, who suddenly had to stop working."* or P5's impression in the main study that people spent time together in the room, *"people live and spend their free time together here"*, even though there was no one present at that moment. This further aligns with the measured increased feeling of social connectedness. It confirms the framework and the potential of traces in VEs to support drawing connections and foster understanding between different dimensions and situations.

5.1.2 Measuring the Success of the Framework

The need to measure the effects of traces was a recurring sub-theme in the expert interviews. Experts pointed out the opportunity for traces to increase specific VE success measures, such as social and spatial presence (e.g., "realness" of the environment). However, they also voiced that VEs compared to PEs allow trace perception to be measured via quantifiable methods, such as gaze tracking. Of course, this is already possible in PE, but with the built-in features of current high-end HMDs, this is more readily available and easier to implement in VE.

Our early results revealed a significant effect regarding (i) the time participants looked at objects in the room with traces and (ii) social presence – supporting **H2**. Although we used social presence in this first exploratory study, we do not claim it to be an all-encompassing variable to measure the traces' effect quantitatively. It does not capture the level of emotional connectedness or users' sensation [58], both dependencies of traces of use reported in PE studies [61, 74, 75]. Given the qualitative user feedback, we hypothesize that these dependencies are indeed affected by the inclusion of traces. However, they are not quantifiable at this stage, which is why we instead suggest social awareness [51] as an additional variable to be measured. Overall, our early results indicate that social VEs benefit from including traces of use. However, future work may explore and include additional quantitative variables, such as social awareness, to measure the full effect of traces.

5.1.3 Including "Time" in the Framework

Due to our study setup, participants were only confronted with a snapshot of traces. This reduced the complexity that would occur by capturing changes over time in, i.e., long-term social VEs with the various user as in Mozilla Hubs [53] or metaverse [46]. Participants noticed the different trace creation times, which were reflected through, e.g., the patina effect on the bench, which accumulated over long-time versus traces resulting from a one-time interaction like the broken glass bottle [23]. However, the exploration of the time dimension was not the focus of our study, as time adds another level of complexity. In line with expert feedback, it exemplary highlights the autonomy of each dimension considered in the framework, i.e., how they independently and through the relationship to other dimensions develop over time. We propose exploring this in future work and considering these dependencies when integrating the framework in the design process.

5.2 Transferring Traces of Use into VE

In the PE, traces of use manifest through tangible and visual material changes over time [63] embedded in materials [23, 61] and environments [1, 30]. Experts rightly questioned whether the materialistic nature of traces can be exploited in the design of social VEs, which mainly rely on vision-based interaction (*"That's why virtual reality is also only visually"; expert four* and *"Simply put, any interaction is technically still very complex."; expert two*). However, our studies indicate that traces' recognizability and persistent characteristics are also evident in VE. The traces enabled users to draw connections to their personal as well as other's prior knowledge, cultural customs, and activities [12, 50] showing that they can support users' in creating social relationships. Additionally, participants in the VE condition engaged significantly longer with the room and thus, the objects within it – supporting **H1, H2**. By focusing on the traces' effect in a VE, we confirm prior work that looked at augmenting traces of use via augmented reality visualization [62] or that augmented PE place through the traces [51]. Furthermore, it shows that the traces of use design space is not only anchored in PE but can be extended along Milgram's reality-virtuality continuum [48], to the far end into VEs. Thus, the traces of use design concept can be seamlessly transferred from PE to VE, and the traces' visual characteristics are similarly perceived and interpreted in VE as in PE.

5.2.1 VR-specific Challenges for Implementing Traces

As a result of the expert interviews and the pre-study, we derived multiple challenges and advantages for implementing traces in VE, namely, implementation effort, developing suitable measurements and to identify approaches to reduce the traces' ambiguity. It introduces questions concerning the tracking of user activities and spatial interactions and how to transform them into a trace. Although participants voiced that they perceived traces made by other humans, experts hypothesized that designing traces in VEs creates uncertainty about their origin. Schneiderman et al. [67] discussed similar concerns and suggested highlighting intelligence through design to differentiate between human vs. AI content. However, as Luck and Aylett [44] point out in their early work on intelligent agents in VEs vs. PE, embedding the user in an immersive experience makes it challenging to differentiate between the virtual agent and the virtual human-controlled avatar. Similar to Bleakly et al. [6], we suggest developing a visual language integrated into the traces that represents who or what is causing the traces. However, whether this uncertainty exists and how to explicitly communicate to users what traces are human- or system-made shall be explored in future work.

5.2.2 VR-specific Advantages for Implementing Traces

In contrast, an advantage is, e.g., that real-world limitations do not restrict VEs considering the transience of materials, the possibilities to track and present hidden information, or traces of wear caused through weather conditions. They provide much more flexibility in the design of traces and the information they convey. Similarly, the traces can be used for analysis purposes for researchers and designers to evaluate the VE's spatial affordance and usage. We imagine that the results could support identifying points of interest, to nudge people into less-visited areas as applied in VR games [21], or to reduce computation power through selective rendering [60]. Altogether, applying the traces in VEs design concept offers advantages for researchers, designers, and users. However, various current limitations require further explorations of how to integrate them.

5.3 The Role of Traces for The Design of Social VEs

Considering the increasing trend toward social VEs, (i.e., [15]), challenges, such as keeping the user engaged [79] and enabling meaningful user-place relationships [15, 76] to foster long-term use, require careful consideration of the VE's spatial design [37]. Our study showed that the traces significantly increased users' feeling of social presence, a contributing and measurable factor for meaningful social VEs [28]. Accordingly, besides an active user manipulation of the VE [37], making other asynchronous users' traces perceivable supported the feeling of connectedness. Besides, as shown in PE studies, spatially integrated traces allow to make assumptions about movement [1, 30, 51] and interaction behavior [33, 61] that may further explain certain cultural customs and norms [32]. When designing for social VEs, one of the challenges will be to design explicit differences between human-made and system-made traces to allow other users to make the right assumptions. Nonetheless, we see the potential in designing with human-made traces in VEs to strengthen a sense of virtual community and customs through the spatial embodiment of shared, common behavior patterns.

Altogether, integrating traces of use in social VEs supports users' feeling of social presence and connectedness, which incorporates the potential of fostering a sense of community. However, VEs introduce other issues than PEs, i.e., trust in the system and identifying the intention of integrating traces. Therefore, it will be up to VR designers to explicitly differentiate between system and user traces.

5.4 The Traces in VE Framework in Practice

The "Traces in VE" framework consolidates learning from PE research and our VE study. We applied the framework to define the design goal and requirements per dimension under the consideration of the dimensions' entanglement. This may be done by asking questions such as "What personas would want to use a shared virtual living space (e.g., Alex who is looking for social contacts)?", "What objects or material changes (e.g., the colored paper) would create meaningful relationships and the relaxing atmosphere of the living room?" or "How would another added object (e.g., a pool table) influence the room atmosphere?". We applied the framework during our iterative design process to continuously review whether the designed components made sense in composition to the other dimensions and adjust where appropriate. For example, the gas-filled balloon changed the spatial affordance by guiding users' attention to the ceiling. This trace of use characteristic (see Table 1) thus, influences a user's VE experience and meaning-making by providing social cues of other users' prior activities and behaviors (such as someone recently filled the balloon with gas). The example also shows the role of the time dimension because a balloon that would already hang halfway to the ground would rather be an indication of less-recent activities. Similarly, a dented couch pillow in AltspaceVR could serve as the trace of time and use that another VE user had been in the VE using the couch recently. In comparison, the traces of use could also be applied to support users in navigating to social gathering places, similar to Albarrak et al. [1]'s work in PE. The framework thereby guides researchers and designers towards focusing on the detailed design decisions that have an essential impact on the user understanding and their VE experience. This includes decisions about what type of trace to implement and what information should be conveyed through the trace. As such, we suggest it as a tool to be integrated into any iterative design process to support decision-making and reveal potentially unaccounted inter-dependencies.

5.5 Limitations

Our study design is limited by evaluating the framework with only four experts and allowing passive exploration of the traces' in VEs. We acknowledge that an active trace creation by the user may influence the user experience. Nonetheless, our study is meant to explore and introduce the traces of use design concept in VE. It serves to initiate the discussion about the concept while showing various future research potentials. Another considerable impact is bandwidth constraints that might heavily increase when keeping users' interaction histories. Our empirical studies also focused on initially exploring the traces' effect in VE. An evaluation of the framework in practice will be done in future work. Lastly, the empirical study results were further reduced by our participant sample being mainly recruited via personal networks. However, we assured that none of the participants had been familiar with the study before.

6 Conclusion and Outlook

Our work conceptualized and explored the PE traces of use design concept for social VEs. The concept is used in interface design to foster meaningful relationships between users, materials, and practices and spatial design to increase users' social awareness and connectedness. To provide a structured, systematic approach to design with traces in VE, we introduce the "Traces in VEs" framework, which is based on theory and validated in four expert interviews. Additionally, we explored the traces in VE' effect in two lab studies (N = 46 in total). The pre-study showed that traces are similarly perceived and interpreted in VE as in PE, whereas the main study confirmed the traces' significant effect on social presence and connectedness. Hence, integrating traces of use in social VEs supports meaningful user experiences and social connectedness.

In future iterations, we want to focus on traces of use deriving through the user's active interaction with a VE and their development over a longer time. By integrating the findings into different social VEs, we will explore their scalability and recognizability in a multi-user, multi-interaction context. Furthermore, it includes research questions such as the duration of a trace's lifetime, i.e., how long it should be presented to the user or how traces would dissolve in VE. Altogether, our work is valuable for practitioners and researchers who systematically want to create social virtual environments.

Acknowledgments

We want to thank our experts and study participants for their valuable input. A special thanks goes to Anna Haller and Anna Anastasia Fischhaber who provided great support in this work's preparation.

References

[1] L. Albarrak, O. Metatla, and A. Roudaut. (don't) mind the step: Investigating the effect of digital social cues on navigation decisions. *Proc. ACM Hum.-Comput. Interact.*, 5(ISS), nov 2021. doi: 10.1145/3488537

[2] S. Alves. Affordances of historic urban landscapes: An ecological understanding of human interaction with the past. *European Spatial Research and Policy*, 21, 12 2014. doi: 10.1515/esrp-2015-0002

[3] J. N. Bailenson, J. Blascovich, A. C. Beall, and J. M. Loomis. Equilibrium theory revisited: Mutual gaze and personal space in virtual environments. *Presence: Teleoperators & Virtual Environments*, 10(6):583–598, 2001.

[4] J. N. Bailenson, J. Blascovich, A. C. Beall, and J. M. Loomis. Interpersonal distance in immersive virtual environments. *Personality and Social Psychology Bulletin*, 29(7):819–833, 2003.

[5] W. Baxter, M. Aurisicchio, and P. Childs. Materials, use and contaminated interaction. *Materials & Design*, 90, 01 2016.

[6] A. Bleakley, V. Wade, and B. R. Cowan. Finally a case for collaborative vr? the need to design for remote multi-party conversations. In *Proceedings of the 2nd Conference on Conversational User Interfaces*, CUI '20. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3405755.3406144

[7] A. Bogner, B. Littig, and W. Menz. *Interviewing Experts*. ECPR Research Methods. Palgrave Macmillan UK, 2009.

[8] V. Braun, V. Clarke, N. Hayfield, and G. Terry. Thematic Analysis BT - Handbook of Research Methods in Health Social Sciences. pp. 843–860, 2019. doi: 10.1007/978-981-10-5251-4_103

[9] K. Chow, C. Coyiuto, C. Nguyen, and D. Yoon. Challenges and design considerations for multimodal asynchronous collaboration in vr. *Proc. ACM Hum.-Comput. Interact.*, 3(CSCW), Nov. 2019. doi: 10.1145/3359142

[10] V. Clarke, N. Hayfield, N. Moller, and I. Tischner. *Once upon a time...: Qualitative story completion methods*, pp. 45–70. 01 2017.

[11] J. M. Cunningham. Mechanizing people and pedagogy: Establishing social presence in the online classroom. *Journal of Asynchronous Learning Network*, 19, 06 2015. doi: 10.24059/olj.v19i3.667

[12] J. Dijk, van. *Creating traces, sharing insight: explorations in embodied cognition design*. PhD thesis, Industrial Design, 2013. doi: 10.6100/IR759609

[13] T. Dong, M. S. Ackerman, and M. W. Newman. "if these walls could talk": Designing with memories of places. In *Proceedings of the 2014 Conference on Designing Interactive Systems*, DIS '14, p. 63–72. Association for Computing Machinery, New York, NY, USA, 2014. doi: 10.1145/2598510.2598605

[14] P. Dourish. Re-space-ing place: "place" and "space" ten years on. In *Proceedings of the 2006 20th Anniversary Conference on Computer Supported Cooperative Work*, CSCW '06, p. 299–308. Association for Computing Machinery, New York, NY, USA, 2006. doi: 10.1145/1180875.1180921

[15] H. Duan, J. Li, S. Fan, Z. Lin, X. Wu, and W. Cai. *Metaverse for Social Good: A University Campus Prototype*, p. 153–161. Association for Computing Machinery, New York, NY, USA, 2021.

[16] L. Dupont, M. Antrop, and V. Van Eetvelde. Eye-tracking analysis in landscape perception research: Influence of photograph properties and landscape characteristics. *Landscape Research*, 39, 07 2014. doi: 10.1080/01426397.2013.773966

[17] D. Egerer and J. van Dijk. Presence mediator: Creating social presence through spatial positioning of everyday objects. 2014. Chi Sparks 2014 : Creating the Difference ; Conference date: 03-04-2014 Through 03-04-2014.

[18] B. Entertainment. World of warcraft, 2004 (last visited Oc. 25th 2021).

[19] W. H. et al. Increasing the feeling of social presence by incorporating realistic interactions in multi-party vr. In *31st International Conference on Computer Animation and Social Agents*, CASA 2018, p. 7–10. ACM, New York, NY, USA, 2018.

[20] A. Fink. Survey research methods. In P. Peterson, E. Baker, and B. McGaw, eds., *International Encyclopedia of Education (Third Edition)*, pp. 152–160. Elsevier, Oxford, third edition ed., 2010. doi: 10.1016/B978-0-08-044894-7.00296-7

[21] G. Games. Horizon zero dawn, 2010(last accessed October 29th, 2021).

[22] C. George, M. Eiband, M. Hufnagel, and H. Hussmann. Trusting strangers in immersive virtual reality. pp. 1–2, 03 2018. doi: 10.1145/3180308.3180355

[23] E. Giaccardi and E. Karana. Foundations of materials experience: An approach for hci. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, p. 2447–2456. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2702123.2702337

[24] E. Giaccardi, E. Karana, H. Robbins, and P. D'Olivo. Growing traces on objects of daily use: A product design perspective for hci. In *Proceedings of the 2014 Conference on Designing Interactive Systems*, DIS '14, p. 473–482. ACM, New York, NY, USA, 2014.

[25] C. I. GmbH. Condens, 2021(last visited Feb. 20th 2022.).

[26] L. GmbH. Limesurvey, 2006(last visited Feb. 20th 2022.).

[27] M. Guimarães, R. Prada, P. A. Santos, J. a. Dias, A. Jhala, and S. Mascarenhas. *The Impact of Virtual Reality in the Social Presence of a Virtual Agent*. Association for Computing Machinery, New York, NY, USA, 2020.

[28] C. Gunawardena and F. Zittle. Social presence as a predictor of satisfaction within a computer-mediated conferencing environment. *American Journal of Distance Education*, 11:8–26, 1997.

[29] Hello Games. No Man's Sky, https://www.nomanssky.com/, 2016 (last accessed October 29th, 2021).

[30] L. Hirsch, E. Economidou, I. Paraschivoiu, and T. Döring. Material meets the city: A materials experience perspective on urban interaction design. *Interactions*, 29(1):58–63, jan 2022. doi: 10.1145/3501358

[31] L. Hirsch, Y. Li, H. Geiger, and A. Butz. Safe-to-touch: Tracking touched areas in public transport. In *Proceedings of 18th IFIP TC13 International Conference On Human-Computer Interaction*, INTERACT'21. Springer LNCS, 2021.

[32] L. Hirsch, B. Rossmy, F. Bemmann, and A. Butz. Affordances based on traces of use in urban environments. In *Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '20)*, TEI '20. ACM, New York, NY, USA, 2020. doi: 10.1145/3374920.3375007

[33] L. Hirsch, B. Rossmy, and A. Butz. Shaping concrete for interaction. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '21. Association for Computing Machinery, New York, NY, USA, 2021. doi: 10.1145/3430524.3440625

[34] T. Innocent and S. Haines. Nonverbal communication in multiplayer game worlds. In *Proceedings of the 4th Australasian Conference on Interactive Entertainment*, IE '07. RMIT University, Melbourne, AUS, 2007.

[35] T. Innocent and S. Haines. Nonverbal communication in multiplayer game worlds. In *Proceedings of the 4th Australasian Conference on Interactive Entertainment*, IE '07. RMIT University, Melbourne, AUS, 2007.

[36] S. Järvelä, B. Cowley, M. Salminen, G. Jacucci, J. Hamari, and N. Ravaja. Augmented virtual reality meditation: Shared dyadic biofeedback increases social presence via respiratory synchrony. *Trans. Soc. Comput.*, 4(2), May 2021. doi: 10.1145/3449358

[37] M. Jonas, S. Said, D. Yu, C. Aiello, N. Furlo, and D. Zytko. Towards a taxonomy of social vr application design. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*, CHI PLAY '19 Extended Abstracts, p. 437–444. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3341215.3356271

[38] Kojima Productions. Death Stranding, https://www.epicgames.com/store/de/p/death-stranding, 2019 (last accessed October 29th, 2021).

[39] M. Kukkakorpi and M. Pantti. A sense of place: Vr journalism and emotional engagement. *Journalism Practice*, 15(6):785–802, 2021. doi: 10.1080/17512786.2020.1799237

[40] J. Laarni, N. Ravaja, T. Saari, S. Böcking, T. Hartmann, and H. Schramm. *Ways to Measure Spatial Presence: Review and Future Directions*, pp. 139–185. Springer International Publishing, Cham, 2015. doi: 10.1007/978-3-319-10190-3_8

[41] M.-H. Lee, O. Son, and T.-J. Nam. Patina-inspired personalization: Personalizing products with traces of daily use. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*, DIS '16, p. 251–263. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2901790.2901812

[42] S. Lee and G. J. Kim. Effects of visual cues and sustained attention on spatial presence in virtual environments based on spatial and object distinction. *Interact. Comput.*, 20(4–5):491–502, sep 2008. doi: 10.1016/j.intcom.2008.07.003

[43] P. C. LP. Gotranskript, 2006 (last visited Feb. 20th 2022).

[44] M. Luck and R. Aylett. Applying artificial intelligence to virtual reality: Intelligent virtual environments. *Applied Artificial Intelligence*, 14(1):3–32, 2000. doi: 10.1080/088395100117142

[45] J. McVeigh-Schultz, A. Kolesnichenko, and K. Isbister. Shaping pro-social interaction in vr: an emerging design framework. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2019.

[46] Meta. Metaverse, https://about.facebook.com/meta/, last accessed January 29th, 2022.

[47] Microsoft Inc. Altspacevr, https://altvr.com, last accessed February 19th, 2022.

[48] P. Milgram, H. Takemura, A. Utsumi, and F. Kishino. Augmented reality: A class of displays on the reality-virtuality continuum. In *Telemanipulator and telepresence technologies*, vol. 2351, pp. 282–292. International Society for Optics and Photonics, 1995.

[49] Miro. Miro, 2011(last visited Feb. 20th 2022).

[50] I. Mols, E. van den Hoven, and B. Eggen. Informing design for reflection: An overview of current everyday practices. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*, NordiCHI '16. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2971485.2971494

[51] B. Monastero and D. K. McGookin. *Traces: Studying a Public Reactive Floor-Projection of Walking Trajectories to Support Social Awareness*, p. 1–13. ACM, New York, NY, USA, 2018.

[52] M. Morozov, A. Gerasimov, M. Fominykh, and A. Smorkalov. *Asynchronous Immersive Classes in a 3D Virtual World: Extended Description of vAcademia*, pp. 81–100. 04 2013. doi: 10.1007/978-3-642-38803-3_5

[53] Mozilla. Mozilla hubs, https://hubs.mozilla.com, last accessed February 19th, 2022.

[54] E. G. Murray, D. L. Neumann, R. L. Moffitt, and P. R. Thomas. The effects of the presence of others during a rowing exercise in a virtual reality environment. *Psychology of Sport and Exercise*, 22:328–336, 2016. doi: 10.1016/j.psychsport.2015.09.007

[55] A. Naz, R. Kopper, R. McMahan, and M. Nadin. Emotional qualities of vr space. pp. 3–11, 01 2017. doi: 10.1109/VR.2017.7892225

[56] B. Nuernberger, K.-C. Lien, L. Grinta, C. Sweeney, M. Turk, and T. Höllerer. Multi-view gesture annotations in image-based 3d reconstructed scenes. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, VRST '16, p. 129–138. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2993369.2993371

[57] Oculus. Oculus Quest, https://www.oculus.com/quest-2/, 2019 (last visited October 29th 2021).

[58] C. S. Oh, J. N. Bailenson, and G. F. Welch. A systematic review of social presence: Definition, antecedents, and implications. *Frontiers in Robotics and AI*, 5:114, 2018. doi: 10.3389/frobt.2018.00114

[59] M. Patton and R. E. C. M. Fund. *Qualitative Research & Evaluation Methods*. SAGE Publications, 2002.

[60] B. Ramic-Brkic, A. Chalmers, A. Sadzak, K. Debattista, and S. Sultanic. Exploring multiple modalities for selective rendering of virtual environments. In *Proceedings of the 29th Spring Conference on Computer Graphics*, SCCG '13, p. 91–98. Association for Computing Machinery, New York, NY, USA, 2013. doi: 10.1145/2508244.2508256

[61] H. Robbins, E. Giaccardi, and E. Karana. Traces as an approach to design for focal things and practices. In *Proceedings of the 9th Nordic Conference*, NordiCHI '16. ACM, New York, NY, USA, 2016.

[62] B. Rogowitz, L. J. Perovich, Y. Li, B. Kierulf, and D. Offenhuber. Touching art – a method for visualizing tactile experience, 2021.

[63] D. K. Rosner, M. Ikemiya, D. Kim, and K. Koch. Designing with traces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*, pp. 1649–1658. ACM Press, New York, New York, USA, 2013.

[64] D. Roth, C. Kleinbeck, T. Feigl, C. Mutschler, and M. Latoschik. Beyond replication: Augmenting social behaviors in multi-user virtual realities. 03 2018. doi: 10.1109/VR.2018.8447550

[65] D. Roth, K. Waldow, F. Stetter, G. Bente, M. Latoschik, and A. Fuhrmann. Siam-c: A socially immersive avatar mediated communication platform. pp. 357–358, 11 2016. doi: 10.1145/2993369.2996302

[66] L. Shih and K. Swan. Fostering social presence in asynchronous online class discussions. In *Proceedings of Th 2005 Conference on Computer Support for Collaborative Learning: Learning 2005: The next 10 Years!*, CSCL '05, p. 602–606. International Society of the Learning Sciences, 2005.

[67] B. Shneiderman. Bridging the gap between ethics and practice: Guidelines for reliable, safe, and trustworthy human-centered ai systems. *ACM Trans. Interact. Intell. Syst.*, 10(4), oct 2020. doi: 10.1145/3419764

[68] M. Slater, S. Neyret, T. Johnston, G. Iruretagoyena, M. Álvarez de la Campa, M. Alabernia, B. Spanlang, and G. Feixas. An experimental study of a virtual reality counselling paradigm using embodied self-dialogue. *Scientific Reports*, 9:10903, 07 2019. doi: 10.1038/s41598-019-46877-3

[69] M. Slater, A. Steed, J. McCarthy, and F. Maringelli. The influence of body movement on subjective presence in virtual environments. *Human factors*, 40:469–77, 10 1998.

[70] H. J. Smith and M. Neff. *Communication Behavior in Embodied Virtual Reality*, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2018.

[71] A. Steed and R. Schroeder. *Collaboration in Immersive and Non-immersive Virtual Environments*, pp. 263–282. Springer International Publishing, Cham, 2015. doi: 10.1007/978-3-319-10190-3_11

[72] A. Steed, M. Spante, I. Heldal, A.-S. Axelsson, and R. Schroeder. Strangers and friends in caves: An exploratory study of collaboration in networked ipt systems for extended periods of time. I3D '03, p. 51–54. Association for Computing Machinery, New York, NY, USA, 2003. doi: 10.1145/641480.641492

[73] T. Teo, G. A. Lee, M. Billinghurst, and M. Adcock. Investigating the use of different visual cues to improve social presence within a 360 mixed reality remote collaboration*. In *The 17th International Conference on Virtual-Reality Continuum and Its Applications in Industry*, VRCAI '19. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3359997.3365687

[74] W.-C. Tsai, D. Orth, and E. van den Hoven. Designing Memory Probes to Inform Dialogue. In *Proceedings of the 2017 Conference on Designing Interactive Systems - DIS '17*, pp. 889–901. ACM Press, New York, New York, USA, 2017. doi: 10.1145/3064663.3064791

[75] W.-C. Tsai and E. van den Hoven. Memory Probes: Exploring Retrospective User Experience Through Traces of Use on Cherished Objects. *International Journal of Design*, 12(3):57–72, 2018.

[76] N. Wagener and J. Niess. *Reflecting on Emotions within VR Mood Worlds*, p. 256–260. Association for Computing Machinery, New York, NY, USA, 2021.

[77] P. Wu, J. Morie, P. Wall, T. Ott, and K. Binsted. Ansible: Virtual reality for behavioral health. *Procedia Engineering*, 159:108–111, 2016. Humanitarian Technology: Science, Systems and Global Impact 2016, HumTech2016. doi: 10.1016/j.proeng.2016.08.132

[78] P. Wu, T. Ott, and J. Morie. Ansible: Social connectedness through a virtual world in an isolated mars simulation mission. In *Proceedings of the 2016 Virtual Reality International Conference*, VRIC '16. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2927929.2927933

[79] A. Yassien, P. El Agroudy, E. Makled, and S. Abdennadher. *A Design Space for Social Presence in VR*. Association for Computing Machinery, New York, NY, USA, 2020.